Chapter 3

LIFE-CYCLE IMPACT ASSESSMENT

Within LCA, the LCI is a well established methodology; however, LCIA methods are less well defined and continue to evolve (Barnthouse *et al.*, 1997; Fava *et al.*, 1993). For toxicity impacts in particular, there are some methods being applied in practice (e.g., toxicity potentials, critical volume, and direct valuation) (Guinee *et al.*, 1996; ILSI, 1996; Curran, 1996), while others are in development. However, there is currently no general consensus among the LCA community as to one method over another. LCIA sophistication has also been discussed in efforts to determine the appropriate level of analytical sophistication for various types of decision making requirements (Bare *et al.*, 1999) or one that adequately addresses toxicity impacts.

Section 3.1 of this chapter presents the University of Tennessee (UT) LCIA methodology, which takes a more detailed approach to chemical toxicity impacts than some methods currently being used. Section 3.1 also discusses data sources, data quality, and the limitations and uncertainties in the LCIA methodology. The UT methodology calculates life-cycle impact category indicators for a number of impact categories, including several traditional LCA impact categories (e.g., global warming, stratospheric ozone depletion, photochemical smog, and energy consumption). Furthermore, the method calculates relative category indicators for potential chronic human health, aquatic ecotoxicity, and terrestrial ecotoxicity impacts in order to address interest in human and ecological toxicity and to fill a common gap in LCIAs. Work conducted for Saturn Corporation and the EPA Office of Research and Development by the UT Center for Clean Products and Clean Technologies has provided the basis for much of this methodology (Swanson, 2001).

Section 3.2 of this chapter describes the data management and analysis software used to calculate LCIA results. Section 3.3 presents the baseline LCIA results for both the CRT and the LCD. Baseline results are presented by impact category and include a discussion of the specific limitations and uncertainties in each category. Section 3.4 presents sensitivity analyses of the baseline results.

3.1 METHODOLOGY

In its simplest form, LCIA is the evaluation of potential impacts to any system as a result of some action. LCIAs generally classify the consumption and loading data from the inventory stage to various impact categories. Characterization methods are then used to quantify the magnitude of the contribution that loading or consumption could have in producing the associated impact. LCIA does not seek to determine actual impacts, but rather to link the data gathered from the LCI to impact categories and to quantify the relative magnitude of contribution to the impact category (Fava *et al.*, 1993; Barnthouse *et al.*, 1997). Further, impacts in different impact categories are generally calculated based on differing scales and therefore cannot be directly compared.

Conceptually, there are three major phases of LCIA, as defined by the Society of Environmental Toxicology and Chemistry (SETAC) (Fava *et al.*, 1993):

- **Classification** - The process of assignment and initial aggregation of data from inventory studies to impact categories (e.g., greenhouse gases or ozone depletion compounds).
- **Characterization** - The analysis and estimation of the magnitudes of potential impacts for each impact category, derived through application of specific impact assessment tools. In the CDP, "impact scores" are calculated for inventory items that have been classified into various impact categories and then aggregated into life-cycle impact category indicators.
- **Valuation** - The assignment of relative values or weights to different impacts and their integration across impact categories to allow decision makers to assimilate and consider the full range of relevant impact scores across impact categories.

The international standard for life cycle impact assessment, ISO 14042, considers classification and characterization to be mandatory elements of LCIA. Valuation or weighting is an optional element to be included depending on the goals and scope of the study. The CDP addresses the first two LCIA steps and leaves the valuation step to industry or others. In addition, further qualitative risk screening of selected materials is conducted beyond the traditional LCIA "characterization" phase in Chapter 4. The methodologies for life-cycle impact classification and characterization are described in Sections 3.1.1 and 3.1.2, respectively. Sections 3.1.3 and 3.1.4 address data sources and data quality, and limitations and uncertainties associated with the LCIA methodology.

3.1.1 Classification

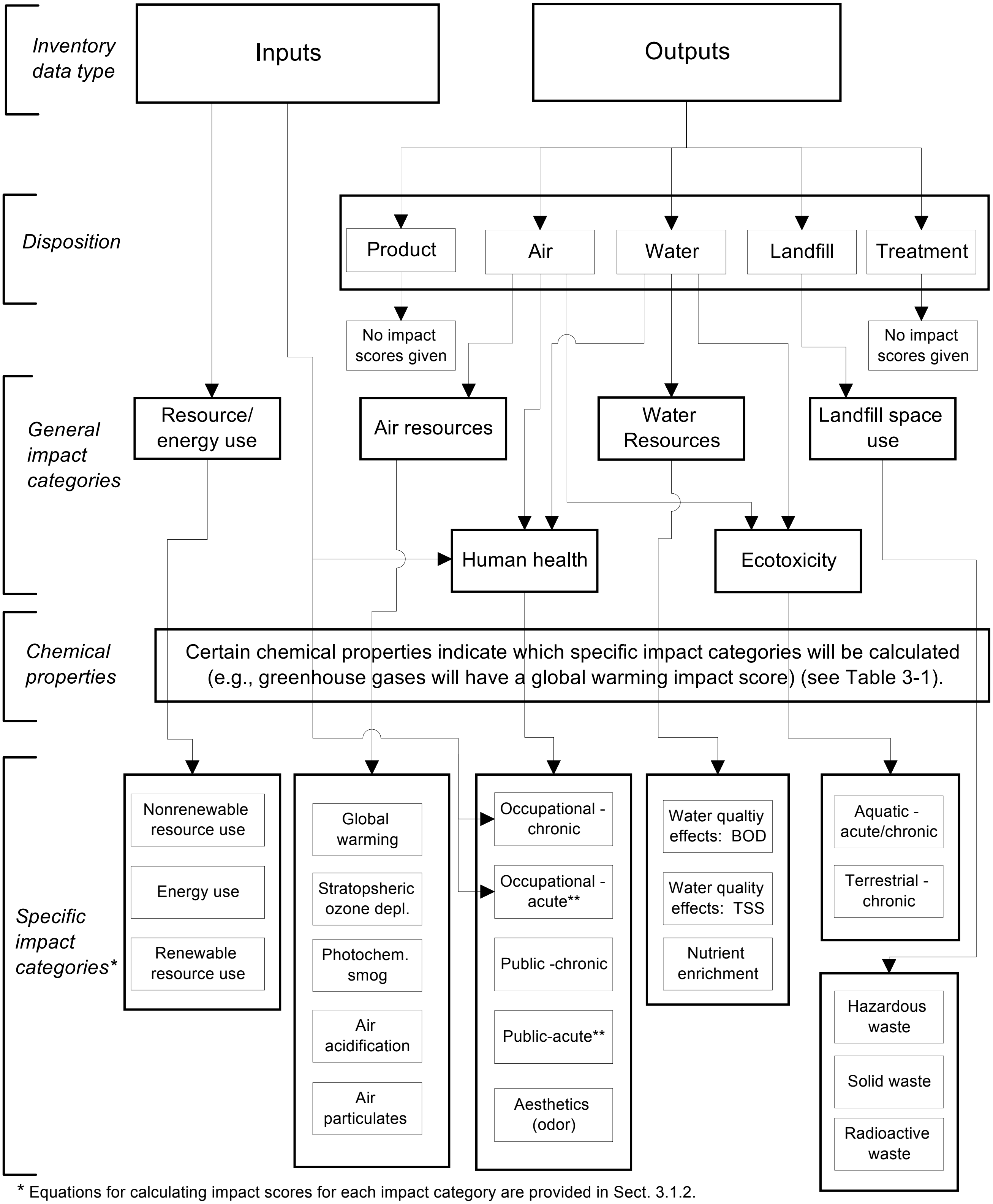
In the first step of classification, impact categories of interest are identified in the scoping phase of the LCA. The categories to be included in the CDP LCIA are listed below:

- Natural Resource Impacts
  - renewable resource use
  - nonrenewable materials use/depletion
  - energy use
  - solid waste landfill use
  - hazardous waste landfill use
  - radioactive waste landfill use
- Abiotic Ecosystem Impacts
  - global warming
  - stratospheric ozone depletion
  - photochemical smog
  - acidification
  - air quality (particulate matter loading)
  - water eutrophication (nutrient enrichment)
  - water quality (biological oxygen demand [BOD] and total suspended solids [TSS])
  - radioactivity

- Potential Human Health and Ecotoxicity Impacts
  - chronic human health effects (occupational and public)
  - aesthetic impacts (odor)
  - aquatic ecotoxicity
  - terrestrial ecotoxicity

The second step of classification is assigning inventory inputs or outputs to applicable impact categories. Classification depends on whether the inventory item is an input or output, what the disposition of the output is, and in some cases the material properties for a particular inventory item. Figure 3-1 shows a conceptual model of classification for the CDP. Table 3-1 presents the inventory types and material properties used to define which impact category will be applicable to an inventory item. One inventory item may have multiple properties and therefore would have multiple impacts. For example, methane is both a global warming gas and has the potential to create photochemical oxidants (smog formation).

Output inventory items from a process may have varying dispositions, such as direct release (to air, water or land), treatment, or recycle/reuse. Outputs with direct release dispositions are classified into impact categories for which impacts will be calculated in the characterization phase of the LCIA. Outputs sent to treatment are considered inputs to a treatment process and impacts are not calculated until direct releases from that process occur. Similarly, outputs to recycle/reuse are considered inputs to previous processes and impacts are not directly calculated for outputs that go to recycle/reuse. Figure 3-1 graphically depicts the relationships between inventory type, dispositions, and impact categories. Note that a product is also an output of a process; however, product outputs are not used to calculate any impacts. Once impact categories for each inventory item are classified, life-cycle impact category indicators are quantitatively estimated through the characterization step.



* Equations for calculating impact scores for each impact category are provided in Sect. 3.1.2.

** Excluded from the scope of the CDP; however, included in the UT Life-Cycle Design Toolkit.

Note, radioactivity (not depicted in this figure) is classified for radioactive isotope outputs to air, water or landfill.

Figure 3-1. Impact classification conceptual model

Table 3-1. Inventory types and properties for classifying inventory items into impact categories

Inventory Type		Chemical/Material Properties	Impact Category
Input	**Output**		
Natural Resource Impacts			
material, water	----	renewable	renewable resource use
material, fuel	----	nonrenewable	nonrenewable resource use/depletion
electricity, fuel	----	energy	energy use
----	solid waste to landfill	RCRA [a] - defined nonhazardous waste (or other country-specific definitions)	solid waste landfill use
----	hazardous waste to landfill	RCRA [a] - defined hazardous waste (or other country-specific definitions)	hazardous waste landfill use
----	radioactive waste to landfill	radioactive waste	radioactive waste landfill use
Abiotic Ecosystem Impacts			
----	air	global warming gases	global warming
----	air	ozone depleting substances	stratospheric ozone depletion
----	air	substances that can be photochemically oxidized	photochemical smog
----	air	substances that react to form hydrogen ions (H+)	acidification
----	air	air particulates (PM_{10}, TSP) [a]	air quality (air particulates)
----	water	substances that contain available nitrogen or phosphorus	water eutrophication (nutrient enrichment)
----	water	BOD [a]	water quality: BOD
----	water	TSS [a]	water quality: TSS
---	radioactivity to air, water, or land	radioactive substance (isotope)	radioactivity
Human Health and Ecotoxicity			
material	----	toxic material	chronic human health effects - occupational
----	air, water	toxic material	chronic human health effects - public
----	air	odorous material	aesthetic impacts (odor)
----	water	toxic material	aquatic ecotoxicity
----	air, water	toxic material	terrestrial ecotoxicity

[a] Acronyms: Resource Conservation and Recovery Act (RCRA); particulate matter with average aerodynamic diameter less than 10 micrometers (PM_{10}); total suspended particulates (TSP); biological oxygen demand (BOD); total suspended solids (TSS).

3.1.2 Characterization

The characterization step of LCIA includes the conversion and aggregation of LCI results to common units within an impact category. Different assessment tools are used to quantify the magnitude of potential impacts, depending on the impact category. Three types of approaches are used in the characterization method for the CDP:

- **Loading** - An impact score is based on the inventory amount.
- **Equivalency** - An impact score is based on the inventory amount weighed by a certain effect, equivalent to a reference chemical.
  - *Full equivalency* - all substances are addressed in a unified, technical model.
  - *Partial equivalency* - a subset of substances can be converted into equivalency factors.
- **Scoring of inherent properties** - An impact score is based on the inventory amount weighed by a score representing a certain effect for a specific material (e.g., toxicity impacts are weighed using a toxicity scoring method).

Table 3-2 lists the characterization approach used with each impact category. The loading approach either uses the direct inventory amount to represent the impact or slightly modifies the inventory amount to change the units into a meaningful loading estimate. Two examples are nonrenewable resource depletion and landfill use. Use of nonrenewable resources are directly estimated as the mass (loading) of that material consumed (input amount). Use of landfill space applies the mass loading of an output of hazardous, nonhazardous, or radioactive waste and converts that loading into a volume to estimate the amount of landfill space consumed.

The equivalency method uses equivalency factors that exist for certain impact categories. Equivalency factors are values that provide a relative measure or weighting that relate an inventory output amount to some impact category relative to a certain chemical. For example, to relate an atmospheric release to the global warming impact category, chemical-specific global warming potential (GWP) equivalency factors are used. GWPs are a measure of the possible warming effect on the earth's surface arising from the emission of a gas relative to carbon dioxide (CO_2). They are based on atmospheric lifetimes and radiative forcing of different greenhouse gases.

The scoring of inherent properties method is applied to impact categories that may have different effects for the same amount of various chemicals, but for which equivalency factors do not exist or are not widely accepted. The scores are meant to normalize the inventory data to provide measures of potential impacts. Scoring methods are employed for the human and ecological toxicity impact categories, based on the CHEMS-1 method described by Swanson et al. (1997), and presented below. The scoring method provides a hazard value (HV) for each potentially toxic material, which is then multiplied by the inventory amount to calculate the toxicity impact score. The aesthetics category directly applies an inherent chemical property (i.e., odor threshold concentration), but does not convert that value into a relative score, or HV.

Using the various approaches, the UT LCIA method calculates impact scores for each inventory item for each applicable impact category. Impact scores are therefore based on either a direct measure of the inventory amount or some modification (e.g., equivalency or scoring) of that amount based on the potential effect the inventory item may have on a particular impact category. Impact scores are then aggregated within each impact category to calculate the various life-cycle impact category indicators.

Inventory amounts are identified on a functional unit basis and then used to calculate impact scores. For each inventory item, an individual score is calculated for each applicable impact category. The equations presented in the subsections that follow calculate impacts for individual inventory items that could later be aggregated as defined by the user. Impact scores represent relative and incremental changes rather than absolute effects or threshold levels.

Table 3-2. LCIA characterization approaches for the CDP

Impact Category	Characterization Approach
Natural Resource Impacts	
Renewable resource use	loading
Nonrenewable materials use/depletion	loading
Energy use	loading
Solid waste landfill use	loading
Hazardous waste landfill use	loading
Radioactive waste landfill use	loading
Abiotic Ecosystem Impacts	
Global warming	equivalency (full)
Stratospheric ozone depletion	equivalency (full)
Photochemical smog	equivalency (partial)
Acidification	equivalency (full)
Air quality (particulate matter)	loading
Water eutrophication (nutrient enrichment)	equivalency (partial)
Water quality (BOD, TSS)	loading
Radioactivity	loading
Human Health and Ecotoxicity	
Chronic human health effects - occupational	scoring of inherent properties
Chronic human health effects - public	scoring of inherent properties
Aesthetic impacts (odor)	application of inherent properties
Aquatic ecotoxicity	scoring of inherent properties
Terrestrial ecotoxicity	scoring of inherent properties

3.1.2.1 Renewable and nonrenewable resource use

Natural resources are materials that are found in nature in their basic form rather than being manufactured (e.g., water, minerals, petroleum and wood). Renewable (or flow) resources, which are those that can be regenerated, are typically biotic resources (e.g., forest products, other plants or animals) and water. Nonrenewable (or stock) resources are abiotic, such as mineral ore or fossil fuels. Both of these natural resource impacts are calculated using the loading approach. Renewable and nonrenewable resource consumption impacts use direct consumption values (i.e., material mass) from the inventory.

Renewable resource impact scores are based on the following process inputs in the LCI: primary, ancillary, water, and fuel inputs of renewable materials. To calculate the loading-based impact scores, the following equation is used:

$$(IS_{RR})_i = [Amt_{RR} \times (1 - RC)]_i$$

where:

IS_{RR}	equals the impact score for use of renewable resource *i* (kg) per functional unit;
Amt_{RR}	equals the inventory input amount of renewable resource *i* (kg) per functional unit; and
RC	equals the fraction recycled content (post industrial and post consumer) of resource *i*.

In the CDP LCI, most manufacturers that provided primary data did not report recycled content nor was the recycled content available for material inventories from secondary sources. Therefore, to calculate the impact score for use of renewable resources the recycled content (RC) was assumed to be zero.

Depletion of materials, which results from the extraction of renewable resources faster than they are renewed, may occur but is not specifically modeled or identified in the renewable resource impact score. For the nonrenewable materials use/depletion category, depletion of materials results from the extraction of nonrenewable resources. Nonrenewable resource impact scores are based on the amount of primary, ancillary, and fuel inputs of nonrenewable materials. To calculate the loading-based impact scores the following equation is used:

$$(IS_{NRR})_i = [Amt_{NRR} \times (1 - RC)]_i$$

where:

IS_{NRR}	equals the impact score for use of nonrenewable resource *i* (NRR) (kg) per functional unit;
Amt_{NRR}	equals the inventory input amount of nonrenewable resource *i* (kg) per functional unit; and
RC	equals the fraction recycled content (post industrial and post consumer) of resource *i*.

Due to the lack of data on the recycled content of nonrenewable resources, RC was assumed to be zero.

3.1.2.2 Energy use

General energy consumption is used as an indicator of potential environmental impacts from the entire energy generation cycle. Energy use impact scores are based on *fuel* and *electricity* inputs. The impact category indicator is the sum of electrical energy inputs and fuel energy inputs. Fuel inputs are converted from mass to energy units using the fuel's heat value (H) and the density (D), presented in Appendix K, Table K-1. The impact score is calculated by:

$$(IS_E)_i = Amt_{Ei} \text{ or } [Amt_F \times (H / D)]_i$$

where:

IS_E	equals the impact score for energy use (MJ) per functional unit;
Amt_E	equals the inventory input amount of electrical energy used (MJ) per functional unit;
Amt_F	equals the inventory input amount of fuel used (kg) per functional unit;
H	equals the heat value of fuel *i* (MJ/L); and
D	equals the density of fuel *i* (kg/L).

This category addresses energy *use* only. The emissions from energy production are outputs from the energy production process and are classified to applicable impact categories, depending on the disposition and chemical properties of the outputs (see Classification Section 3.1.1).

3.1.2.3 Landfill use

Landfill impacts are calculated using solid, hazardous, or radioactive waste outputs to land as volume of landfill space consumed. Solid waste landfill use pertains to the use of suitable and designated landfill space as a natural resource where municipal waste or construction debris is accepted. A solid waste landfill impact score is calculated using solid waste outputs disposed of in a solid waste (nonhazardous) landfill. Impact characterization is based on the volume of solid waste, determined from the inventory mass amount of waste and material density of each specific solid waste type:

$$(IS_{SWL})_i = (Amt_{SW} / D)_i$$

where:

IS_{SWL}	equals the impact score for solid waste landfill (SWL) use for waste *i* (m^3) per functional unit;
Amt_{SW}	equals the inventory output amount of solid waste *i* (kg) per functional unit; and
D	equals density of waste *i* (kg/m^3).

Hazardous waste landfill use pertains to the use of suitable and designated landfill space as a natural resource where hazardous waste, as designated and regulated under the Resource Conservation and Recovery Act, is accepted. For non-US activities, equivalent hazardous or special waste landfills are considered for this impact category. Impact scores are characterized from hazardous waste outputs with a disposition of landfill. Impact characterization is based on the volume of hazardous waste, determined from the inventory mass amount of waste and material density of each specific hazardous waste type:

$$(IS_{HWL})_i = (Amt_{HW} / D)_i$$

where:

IS_{HWL}	equals the impact score for hazardous waste landfill (HWL) use for waste *i* (m^3) per functional unit;
Amt_{HW}	equals the inventory output amount of hazardous waste *i* (kg) per functional unit; and
D	equals density of waste *i* (kg/m^3).

Radioactive waste pertains to the suitable and designated landfill space as a natural resource that accepts radioactive waste. Impacts are characterized from radioactive waste outputs with a disposition of landfill. Impact characterization is based on the volume of radioactive waste, determined from the inventory mass amount of waste and material density of each specific waste.

$$(IS_{RWL})_i = (Amt_{RW}/D)_i$$

where:

IS_{RWL}	equals the impact score for radioactive waste landfill (RWL) use for waste *i* (m^3) per functional unit;
Amt_{RW}	equals the inventory output amount of radioactive waste *i* (kg) per functional unit; and
D	equals density of waste *i* (kg/m^3).

3.1.2.4 Global warming impacts

The build up CO_2 and other greenhouse gases in the atmosphere may generate a "greenhouse effect" of rising temperature and climate change. Global warming potential (GWP) refers to the warming (relative to CO_2) that chemicals contribute to this effect by trapping the earth's heat. The impact scores for global warming (global climate change) effects are calculated using the mass of a global warming gas released to air modified by a GWP equivalency factor. The GWP equivalency factor is an estimate of a chemical's atmospheric lifetime and radiative forcing that may contribute to global climate change compared to the reference chemical CO_2. Therefore, GWPs are in units of CO_2 equivalents. GWPs have been published for known global warming chemicals within differing time horizons. The LCIA methodology being presented in this memorandum uses GWPs having effects in the 100-year time horizon. Although LCA does not necessarily have a temporal component of the inventory, these impacts are expected to be far enough into the future that releases occurring throughout the life cycle of a computer monitor would be within the 100-year time frame. Appendix K, Table K-2 presents a current list of GWPs as identified by the Intergovernmental Panel on Climate Change (IPCC) (Houghton et al., 1996). Global warming impact scores are calculated for any chemicals in the LCI that are found in Appendix K, Table K-2. The equation to calculate the impact score for an individual chemical is as follows:

$$(IS_{GW})_i = (EF_{GWP} \ x \ Amt_{GG})_i$$

where:

IS_{GW} equals the global warming impact score for greenhouse gas chemical i (kg CO_2 equivalents) per functional unit;

EF_{GWP} equals the GWP equivalency factor for greenhouse gas chemical i (CO_2 equivalents, 100 year time horizon) (Appendix K, Table K-2); and

Amt_{GG} equals the inventory output amount of greenhouse gas chemical i released to air (kg) per functional unit.

3.1.2.5 Stratospheric ozone depletion

The stratospheric ozone layer filters out harmful ultraviolet radiation from the sun. Chemicals such as chlorofluorocarbons, if released to the atmosphere, may result in ozone-destroying chemical reactions. Stratospheric ozone depletion refers to the release of chemicals that may contribute to this effect. Impact scores are based on the identity and amount of ozone depleting chemicals released to air. Currently identified ozone depleting chemicals are those with ozone depletion potentials (ODPs), which measure the change in the ozone column in the equilibrium state of a substance compared to the reference chemical chlorofluorocarbon (CFC)-11 (Heijungs *et al.*, 1992; CAAA, 1990). The list of ODPs that are used in this methodology are provided in Appendix K, Table K-3. The individual chemical impact score for stratospheric ozone depletion impacts is based on the ODP and inventory amount of the chemical:

$$(IS_{OD})_i = (EF_{ODP} \, x \, Amt_{ODC})_i$$

where:

IS_{OD} equals the ozone depletion impact score for chemical i (kg CFC-11 equivalents) per functional unit;

EF_{ODP} equals the ODP equivalency factor for chemical i (CFC-11 equivalents) (Appendix K, Table K-3); and

Amt_{ODC} equals the amount of ozone depleting chemical i released to air (kg) per functional unit.

3.1.2.6 Photochemical smog

Photochemical oxidants are produced in the atmosphere from sunlight reacting with hydrocarbons and nitrogen oxides. At higher concentrations they may cause or aggravate health problems, plant toxicity, and deterioration of certain materials. Photochemical oxidant creation potential (POCP) refers to the release of chemicals that may contribute to this effect. The POCP is based on simulated trajectories of tropospheric ozone production with and without volatile organic carbons (VOCs) present. The POCP is a measure of a specific chemical compared to the reference chemical ethene (Heijungs *et al.*, 1992). The list of chemicals with POCPs to be used in this methodology are presented in Appendix K, Table K-4. As shown in Table 3-2, photochemical smog impacts are based on partial equivalency because some chemicals cannot be converted into POCP equivalency factors. For example, nitrogen oxides do not have a POCP. However, VOCs are assumed to be the limiting factor and if VOCs are present, there is a potential impact. Impact scores are based on the identity and amount of chemicals with POCP equivalency factors released to the air and the chemical-specific equivalency factor:

$$(IS_{POCP})_i = (EF_{POCP} \; x \; Amt_{POC})_i$$

where:

IS_{POCP}	equals the photochemical smog impact score for chemical *i* (kg ethene equivalents) per functional unit;
EF_{POCP}	equals the POCP equivalency factor for chemical *i* (ethene equivalents) (Appendix K, Table K-4); and
Amt_{POC}	equals the amount of smog-creating chemical *i* released to the air (kg) per functional unit.

3.1.2.7 Acidification

This refers to the release of chemicals that may contribute to the formation of acid precipitation. Impact characterization is based on the amount of a chemical released to air that would cause acidification and the acidification potentials (AP) equivalency factor for that chemical. The AP equivalency factor is the number of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released compared to sulfur dioxide (SO_2) (Heijungs *et al.*, 1992; Hauschild and Wenzel, 1997). Appendix K, Table K-5 lists the AP values that will be used as the basis of calculating acidification impacts. The impact score is calculated by:

$$(IS_{AP})_i = (EF_{AP} \; x \; Amt_{AC})_i$$

where:

IS_{AP}	equals the impact score for acidification for chemical *i* (kg SO_2 equivalents) per functional unit;
EF_{AP}	equals the AP equivalency factor for chemical *i* (SO_2 equivalents) (Appendix K, Table K-5); and
Amt_{AC}	equals the amount of acidification chemical *i* released to the air (kg) per functional unit.

3.1.2.8 Air particulates

This refers to the release and build up of particulate matter primarily from combustion processes. Impact scores are based on particulate release amounts [particulate matter with average aerodynamic diameter less than 10 micrometers (PM_{10})] to the air. This size of particulate matter is most damaging to the respiratory system. Impact characterization is simply based on the inventory amount of particulates released to air. This loading impact score is calculated by:

$$IS_{PM} = Amt_{PM}$$

where:

IS_{PM}	equals impact score for particulates (kg PM_{10}) per functional unit, and

Amt_{PM}	equals the inventory output amount of particulate release (PM_{10}) to the air (kg) per functional unit.

In this equation, PM_{10} is used to estimate impacts. However, if only total suspended particulates (TSP) data are available, these data may be used. Note that using TSP data is an overestimation of $PM_{10,}$ which only refers to the fraction of particulates in the size range below 10 micrometers. A common conversion factor (TSP to PM_{10}) is not available because the fraction of PM_{10} varies depending on the type of particulates.

3.1.2.9 Water eutrophication

Eutrophication (nutrient enrichment) impacts to water are based on the identity and concentrations of eutrophication chemicals released to surface water after treatment. Equivalency factors for eutrophication have been developed assuming nitrogen (N) and phosphorus (P) are the two major limiting nutrients of importance to eutrophication. Therefore, the partial equivalencies are based on the ratio of N to P in the average composition of algae ($C_{106}H_{263}O_{110}N_{16}P$) compared to the reference compound phosphate (PO_4^{3-}) (Heijungs *et al.*, 1992; Lindfors *et al.*, 1995). If the wastewater stream is first sent to a publicly owned treatment works (POTW), treatment is considered as a separate process and the impact score would be based on releases from the POTW to surface waters. Impact characterization is based on eutrophication potentials (EP) (Appendix K, Table K-6) and the inventory amount:

$$(IS_{EUTR})_i = (EF_{EP} \times Amt_{EC})_i$$

where:

IS_{EUTR}	equals the impact score for regional water quality impacts from chemical *i* (kg phosphate equivalents) per functional unit;
EF_{EP}	equals the EP equivalency factor for chemical *i* (phosphate equivalents) (Appendix K, Table K-6); and
Amt_{EC}	equals the inventory output mass (kg) of chemical *i* per functional unit of eutrophication chemical in a wastewater stream released to surface water after any treatment, if applicable.

3.1.2.10 Water quality

Water quality impacts are characterized as surface water impacts due to releases of wastes causing oxygen depletion and increased turbidity. Two water quality impact scores are calculated based on the biological oxygen demand (BOD) and total suspended solids (TSS) in the wastewater streams released to surface water. The impact scores are based on releases to surface water following any treatment. Using a loading characterization approach, impact characterization is based on the amount of BOD and TSS in a wastewater stream. The water quality score equations for each are presented below:

$$(IS_{BOD})_i = (Amt_{BOD})_i$$

and

$$(IS_{TSS})_i = (Amt_{TSS})_i$$

where:
IS_{BOD} equals the impact score for BOD water quality impacts for waste stream i (kg) per functional unit;
Amt_{BOD} equals the inventory output amount of BOD in wastewater stream i released to surface waters (kg) per functional unit;
IS_{TSS} equals the impact score for TSS water quality impacts for waste stream i (kg) per functional unit; and
Amt_{TSS} equals the inventory amount of TSS in wastewater stream i released to surface waters (kg) per functional unit.

3.1.2.11 Radioactivity

Radioactivity inventoried as the quantity of an isotope released to the environment is considered in the radioactivity impact category. These outputs, such as those from the generation of nuclear energy, can be air, water, or land releases. The radioactivity impact is a direct loading score measured in Bequerels of radioactivity, and calculated as follows:

$$(IS_{rad})_i = (Amt_{rad})_i$$

where:
IS_{rad} equals the impact score for radioactivity of isotope i (Bq) per functional unit; and
Amt_{rad} equals the inventory amount of radioactivity of isotope i (Bq) per functional unit.

While this impact category uses a loading approach, further refinement of this impact score calculation in the future could use radioactivity dose conversion factors, which convert radioactivity quantities (e.g., Bq) into human doses equivalents (e.g., sievert or rem).

3.1.2.12 Potential human health impacts

Human health impacts are defined in the context of life-cycle assessment as relative measures of potential adverse health effects to humans. Human health impact categories included in the scope of this LCA are chronic (repeated dose) effects, which include noncarcinogenic and carcinogenic effects, and aesthetics (although not a health effect *per se*, aesthetics pertains to human welfare). Chronic human health effects to both workers and the public are considered. Quantitative measures of consumer impacts are not included in this LCIA methodology because there are no direct outputs quantified in the LCI from the use stage of a computer monitor. The CDP does, however, quantify indirect outputs from energy consumption (i.e., pollutants released from energy production). In addition, Appendix L qualitatively discusses direct consumer impacts, such as electromagnetic radiation or eye strain.

The chemical characteristic that classifies inventory items to the human health effects (and ecotoxicity) categories is toxicity. Toxic chemicals were identified by searching lists of toxic chemicals [e.g., Toxic Release Inventory (TRI)] and if needed, toxicity databases [e.g., Hazardous Substances Data Bank (HSDB)], and Registry of Toxic Effects of Chemical Substances (RTECS), or other literature. Upon review by the EPA DfE Workgroup (see Appendix C), several materials in the CDP inventory were excluded from the toxic list if they are generally accepted as nontoxic. The EPA DfE Workgroup also reviewed the list of chemicals that were included in this project as potentially toxic. The list of potentially toxic chemicals is provided in Appendix K, Table K-8, and chemicals that were excluded from the toxic list that appear in the CDP inventory are presented in Appendix K, Table K-9.

Human (and ecological) toxicity impact scores are calculated based on a chemical scoring method modified from CHEMS-1 found in Swanson *et al.* (1997). To calculate impact scores, chemical-specific inventory data are required. Any chemical that is assumed to be potentially toxic is given a toxicity impact score. If toxicity data are unavailable for a chemical, a mean default toxicity score is given. This is described in further detail below. Ecological toxicity is presented in Section 3.1.2.13.

Chronic human health effects are potential human health effects occurring from repeated exposure to toxic agents over a relatively long period of time (i.e., years). These effects could include carcinogenicity, reproductive toxicity, developmental effects, neurotoxicity, immunotoxicity, behavioral effects, sensitization, radiation effects, chronic effects to other specific organs or body systems (e.g., blood, cardiovascular, respiratory, kidney and liver effects). Impact categories for chronic health effects are divided into worker and public impacts. Occupational impact scores are based on inventory inputs and public impact scores are based on inventory outputs.

Chronic occupational health effects

This refers to potential health effects to workers, including cancer, from long-term repeated exposure to toxic or carcinogenic agents in an occupational setting. For possible occupational impacts, the identity and amounts of materials/constituents as input to a process are used. The inputs represent potential exposures and we could assume that a worker would continue to work at a facility and incur exposures over time. However, the inventory is based on manufacturing one monitor and does not truly represent chronic exposure. Therefore, the chronic health effects impact score is more a ranking of the potential of a chemical to cause chronic effects than a prediction of actual effects.

Chronic occupational health effects scores are based on the identity of toxic chemicals (or chemical ingredients) found in primary and ancillary inputs from materials processing and manufacturing life-cycle stages. The distinction between pure chemicals and mixtures is made implicitly, if possible, by specifying component ingredients of mixtures in the inventory.

The chronic human health impact scores are calculated using hazard values (HVs) for carcinogenic and for noncarcinogenic effects. The former HV uses cancer slope factors or cancer weight of evidence (WOE) classifications assigned by EPA and/or the International Agency for Research on Cancer (IARC) when no slope factor exists. If both an oral and inhalation slope factor exist, the slope factor representing the larger hazard is chosen. Where no slope factor is available for a chemical, but there is a WOE classification, the WOE is used to designate default hazard values as follows: EPA WOE Groups D (not classifiable) and E (noncarcinogen) and IARC Groups 3 (not classifiable) and 4 (probably not carcinogenic) are given a hazard value of zero. All other WOE classifications (known, probable, and possible human carcinogen) are given a default HV of 1 (representative of a mean slope factor) (Table 3-3). Similarly, materials for which no cancer data exist, but are designated as potentially toxic, are also given a default value of 1.

Table 3-3. Hazard values for carcinogenicity weight-of-evidence if no slope factor is available

EPA Classification	IARC Classification	Description	Hazard Value
Group A	Group 1	known human carcinogen	1
Group B1	Group 2A	Probable human carcinogen (limited human data)	1
Group B2	N/A	Probable human carcinogen (from animal data)	1
Group C	Group 2B	Possible human carcinogen	1
Group D	Group 3	Not classifiable	0
Group E	Group 4	Noncarcinogenic or probably not carcinogenic	0

N/A: not applicable.

The cancer hazard value for chronic occupational health effects is the greater of the following:

$$\textit{oral}: \quad (HV_{CA_{oral}})_i = \frac{oral\ SF_i}{oral\ SF_{mean}}$$

$$\textit{inhalation}: \quad (HV_{CA_{inhalation}})_i = \frac{inhalation\ SF_i}{inhalation\ SF_{mean}}$$

where:

HV_{CAoral}	equals the cancer oral hazard value for chemical *i* (unitless);
$oral\ SF_i$	equals the cancer oral slope factor for chemical *i* (mg/kg-day);
$oral\ SF_{mean}$	equals the geometric mean cancer slope factor of all available slope factors (0.71 mg/kg-day);
$HV_{CAinhalation}$	equals the cancer inhalation hazard value for chemical *i* (unitless);
$inhalation\ SF_i$	equals the cancer inhalation slope factor for chemical *i* $(mg/kg\text{-}day)^{-1}$; and
$inhalation\ SF_{mean}$	equals the geometric mean cancer inhalation slope factor of all available inhalation slope factors (1.70 $mg/kg\text{-}day)^{-1}$.

The oral and inhalation slope factor mean values are the geometric means of a set of chemical data presented in Appendix K, Table K-10.

The noncarcinogen HV is based on either no-observed-adverse-effect levels (NOAELs) or lowest-observed-adverse-effect levels (LOAELs). The noncarcinogen HV is the greater of the

$$\textit{oral}: \quad (HV_{NC_{oral}})_i = \frac{1/(oral\ NOAEL_i)}{1/(oral\ NOAEL_{mean})}$$

inhalation and oral HV:

$$\textit{inhalation}: \quad (HV_{NC_{inhalation}})_i = \frac{1/(inhal\ NOAEL_i)}{1/(inhal\ NOAEL_{mean})}$$

where:

$HV_{NC\ oral}$	equals the noncarcinogen oral hazard value for chemical *i* (unitless);
$oralNOAEL_i$	equals the oral NOAEL for chemical *i* (mg/kg-day);
$oralNOAEL_{mean}$	equals the geometric mean oral NOAEL of all available oral NOAELs (11.88 mg/kg-day);
$HV_{NC\ inhalation}$	equals the noncarcinogen inhalation hazard value for chemical *i* (unitless);
$inhalNOAEL_i$	equals the inhalation NOAEL for chemical *i* (mg/m^3); and
$inhalNOAEL_{mean}$	equals the geometric mean inhalation NOAEL of all available inhalation NOAELs (68.67 mg/kg-day).

The oral and inhalation NOAEL mean values are the geometric means of a set of chemical data presented in Appendix K, Table K-8. If LOAEL data are available instead of NOAEL data, the LOAEL divided by 10 is used to substitute for the NOAEL. The most sensitive endpoint is used if there are multiple data for one chemical.

The sum of the carcinogen and noncarcinogen HVs for a particular chemical is multiplied by the applicable inventory input to calculate the impact score:

$$(IS_{CHO})_i = [(HV_{CA} + HV_{NC},)\ x\ Amt_{TCinput}]_i$$

where:

IS_{CHO}	equals the impact score for chronic occupational health effects for chemical *i* (tox-kg) per functional unit;
HV_{CA}	equals the hazard value for carcinogenicity for chemical *i*;
HV_{NC}	equals the hazard value for chronic noncancer effects for chemical *i*; and
$Amt_{TCinput}$	equals the amount of toxic inventory input (kg) per functional unit for chemical *i*.

Chronic public health effects

For chronic public health effects, the impact score represents a surrogate for potential health effects to residents living near a facility, including cancer, from long-term repeated exposure to toxic or carcinogenic agents. Impact scores are based on the identity and amount of toxic chemical outputs with dispositions to air and water.[1] As stated above, inventory items do not truly represent long-term exposure; instead, impacts are relative toxicity weightings of the inventory.

The scores for impacts to the public differ from the occupational impacts in that inventory outputs are used as opposed to inventory inputs. Note that this basic screening level scoring does not incorporate the fate and transport of the chemicals. The chronic public health effects impact score is calculated as follows:

$$(IS_{CHP})_i \;=\; [(HV_{CA} + HV_{NC}) \text{ x } Amt_{TCoutput}]_i$$

where:

IS_{CHP} equals the impact score for chronic human health effects to the public for chemical *i* (tox-kg) per functional unit; and

$Amt_{TCoutput}$ equals the amount of toxic inventory output of chemical *i* to air and water (kg) per functional unit.

Aesthetic impacts (odor)

This refers to impacts that detract from the quality of the local environment from a human perspective. Characterization in this project is based on odor. Impact scores are based on the identity and amount of odor-causing chemicals (Heijungs *et al.*, 1992; EPA 1992), released to the air and their odor threshold value (OTV) (Heijungs *et al.*, 1992) (Appendix K, Table K-7). This approach does not score chemicals as is done for toxic chemicals. The OTV is specific to a chemical, but does not use an equivalency factor that is based on a reference chemical or a hazard value based on a mean OTV. In this case, the OTV is a concentration which, when divided into the mass output of a chemical, results in an impact score in units of volume of malodorous air:

$$(IS_{AS})_i \;=\; (Amt_{OC} / OTV)_i$$

where:

IS_{AS} equals the aesthetics impact score for chemical *i* (m^3 malodorous air) per functional unit;

Amt_{OC} equals the amount of odor-causing output for chemical *i* released to air (mg) per functional unit; and

OTV equals the odor threshold value for chemical *i* (mg/m^3) (Appendix K, Table K-10).

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[1] Disposition could be to groundwater. For example, a landfill model could have releases that go to groundwater.

Note that this impact assessment methodology determines the volume of malodorous air created if there is no dilution. In reality, many of the air releases reported in the LCI may occur at concentrations below the chemical's odor threshold.

3.1.2.13 Ecotoxicity

Ecotoxicity refers to effects of chemical outputs on nonhuman living organisms. Impact categories include ecotoxicity impacts to aquatic and terrestrial ecosystems.

Aquatic toxicity

Toxicity measures for fish are used to represent potential adverse effects to organisms living in the aquatic environment from exposure to a toxic chemical. Impact scores are based on the identity and amount of toxic chemicals as outputs to surface water. Impact characterization is based on CHEMS-1 acute and chronic hazard values for fish (Swanson *et al.*, 1997) combined with the inventory amount. Both acute and chronic impacts are combined into the aquatic toxicity term. The hazard values (HVs) for acute and chronic toxicity are based on LC_{50} and NOAEL toxicity data, respectively, mostly from toxicity tests in fathead minnows (*Pimephales promelas*) (Swanson *et al.*, 1997). The acute fish HV is calculated by:

$$(HV_{FA})_i = \frac{1/(LC_{50})_i}{1/(LC_{50})_{mean}}$$

where:

HV_{FA}	equals the hazard value for acute fish toxicity for chemical *i* (unitless);
LC_{50i}	equals the lethal concentration to 50% of the exposed fish population for chemical *i*; and
LC_{50mean}	equals the geometric mean LC_{50} of available fish LC_{50} values in Appendix K, Table K-8 (23.45 mg/L).

The chronic fish HV is calculated by:

$$(HV_{FC})_i = \frac{1/NOAEL_i}{1/NOAEL_{mean}}$$

where:

HV_{FC}	equals the hazard value for chronic fish toxicity for chemical *i*;
$NOAEL_i$	equals the no observed adverse affect level for fish for chemical *i*; and
$NOAEL_{mean}$	equals the geometric mean NOAEL of available fish NOAEL values in Appendix K, Table K-7 (3.90 mg/L).

The aquatic toxicity impact score is calculated as follows:

$$(IS_{AQ})_i = [(HV_{FA} + HV_{FC}) \text{ x } Amt_{TCoutput,water}]_i$$

where:

IS_{AQ}	equals the impact score for aquatic ecotoxicity for chemical *i* (tox-kg) per functional unit; and
$Amt_{TCoutput,water}$	equals the toxic inventory output amount of chemical *i* to water (kg) per functional unit.

Terrestrial toxicity

Toxicity measures for mammals (primarily rodents) are used to represent potential adverse effects to organisms living in the terrestrial environment from exposure to a toxic chemical. Impact scores are based on the identity and amount of toxic chemicals as outputs to air and surface water. Impact characterization is based on chronic toxicity hazard values combined with the inventory amount. The terrestrial toxicity impact score is based on the same noncancer chronic data used for human health because underlying data are from the same mammal studies (see Section 2.1.2.12 for the HV_{NC} term). The cancer hazard value was not included in the terrestrial impact score as it is based on ranking for potential human carcinogenicity. The terrestrial toxicity impact score is as follows:

$$(IS_{TER})_i = (HV_{NC} \text{ x } Amt_{TCoutput})_i$$

where:

IS_{TER}	equals the impact score for terrestrial toxicity for chemical *i* (tox-kg) per functional unit; and
$Amt_{TCoutput}$	equals the toxic inventory output amount of chemical *i* (kg) per functional unit.

3.1.2.14 Summary of impact score equations

Table 3-4 summarizes the impact categories, associated impact score equations, and the input or output data required for calculating natural resource impacts. Each of these characterization equations are loading estimates.

Table 3-4. Summary of natural resources impact scoring

Impact Category	Impact Score Approach	Data Required from Inventory (per functional unit)	
		Inputs	**Outputs**
Use of renewable resources	$IS_{RR} = Amt_{RR} \times (1 - RC)$	Material mass (kg) (e.g., water)	none
Use/depletion of nonrenewable materials	$IS_{NRR} = Amt_{NRR} \times (1 - RC)$	Material mass (kg)	none
Energy use, general energy consumption	$IS_E = Amt_E$ or $(Amt_F \times H/D)$	Energy (MJ) (electricity, fuel)	none
Solid waste landfill use	$IS_{SWL} = Amt_{SW} / D$	none	solid waste mass (kg) and density (i.e., volume, m^3)
Hazardous waste landfill use	$IS_{HWL} = Amt_{HW} / D$	none	hazardous waste mass (kg) and density (i.e., volume, m^3)
Radioactive waste landfill use	$IS_{RWL} = Amt_{RW} / D$	none	radioactive waste mass (kg) and density (i.e., volume, m^3)

Abbreviations: RC = recycled content; H = heat value of fuel *i*; D = density of fuel *i*.

The term abiotic ecosystem refers to the nonliving environment that supports living systems. Table 3-5 presents the impact categories, impact score equations, and inventory data requirements for abiotic environmental impacts to atmospheric resources.

Table 3-5. Summary of atmospheric resource impact scoring

Impact Category	Impact Score Approach	Data Required from Inventory (per functional unit)	
		Inputs	**Outputs**
Global warming	$IS_{GW} = EF_{GWP} \times Amt_{GG}$	none	amount of each greenhouse gas chemical released to air
Stratospheric ozone depletion	$IS_{OD} = EF_{ODP} \times Amt_{ODC}$	none	amount of each ozone depleting chemical released to air
Photochemical smog	$IS_{POCP} = EF_{POCP} \times Amt_{POC}$	none	amount of each smog-creating chemical released to air
Acidification	$IS_{AP} = EF_{AP} \times Amt_{AC}$	none	amount of each acidification chemical released to air
Air quality (particulate matter)	$IS_{PM} = Amt_{PM}$	none	amount of particulates: PM_{10} or TSP released to air [a]

[a] Assumes PM_{10} and TSP are equal; however, using TSP will overestimate PM_{10}.

Table 3-6 presents the impact categories, impact score equations, and required inventory data for abiotic environmental impacts to water resources.

Table 3-6. Summary of water resource impact scoring

Impact Category	Impact Score Approach	Data Required from Inventory (per functional unit)	
		Inputs	Outputs
Water eutrophication	$IS_{EUTR} = EF_{EP} \times Amt_{EC}$	none	amount of each eutrophication chemical released to water
Water quality (BOD)	$IS_{BOD} = Amt_{BOD}$	none	amount of BOD in each wastewater stream released to surface water
Water quality (TSS)	$IS_{TSS} = Amt_{TSS}$	none	amount of suspended solids (TSS) in each wastewater stream released to surface water

Table 3-7 summarizes the human health and ecotoxicity impact scoring approaches. The impact categories, impact score equations, the type of inventory data, and the chemical properties required to calculate impact scores are presented. The human health effects and ecotoxicity impact scores are based on the scoring of inherent properties approach to characterization.

Table 3-7. Summary of human health and ecotoxicity impact scoring

Impact Category	Impact Score Equations	Data Required from Inventory (per functional unit)		Chemical Properties Data Required
		Inputs	Outputs	
Chronic human health effects - occupational	$IS_{CHO} = (HV_{CA} + HV_{NC}) \times Amt_{TCinput}$	mass of each primary and ancillary toxic chemical	none	WOE or SF and/or mammal NOAEL or LOAEL
Chronic human health effects - public	$IS_{CHP} = (HV_{CA} + HV_{NC}) \times Amt_{TCoutput}$	none	mass of each toxic chemical released to air and surface water	WOE or SF and/or mammal NOAEL or LOAEL
Aesthetic impacts (odor)	$IS_{AS} = Amt_{OC} / OTV$	none	mass of odorous chemicals released to air	human odor threshold values
Aquatic toxicity	$IS_{AQ} = (HV_{FA} + HV_{FC}) \times Amt_{TCoutput,water}$	none	mass of each toxic chemical released to surface water	fish LC_{50} and/or fish NOAEL
Terrestrial toxicity	$IS_{TER} = HV_{NC} \times Amt_{TCoutput}$	none	mass of each toxic chemical released to air or surface water	mammal NOAEL

3.1.2.15 Aggregation of impact scores

Individual impact scores are calculated for inventory items for a certain impact category and can be aggregated by inventory item (e.g., a certain chemical), process, life-cycle stage, or entire product profile. For example, global warming impacts can be calculated for one inventory item (e.g., CO_2 releases), for one process that could include contributions from several inventory items (e.g., electricity generation), for a life-cycle stage that may consist of several process steps (e.g., product manufacturing), or for an entire profile (e.g., a CRT desktop monitor over its life).

The following example illustrates how impacts are calculated. If two toxic chemicals [e.g., toluene and benzo(a)pyrene] are included in a waterborne release to surface water from Process A, impact scores would be calculated for the following impact categories (based on the classification shown in Table 3-1):

- Chronic public health effects;
- Aquatic toxicity; and
- Terrestrial toxicity.

Despite the output types being waterborne releases, the water eutrophication and water quality impact categories are not applicable here because the chemical properties criteria in Table 3-1 are not met. That is, these chemicals do not contain N or P and are not themselves wastewater streams.

Using chronic public health effects as an example, impact scores are then calculated for each chemical as follows:

$$IS_{CHP:toluene} = (HV_{CA:toluene} + HV_{NC:toluene}) \text{ x } Amt_{TCoutput:toluene}$$
$$IS_{CHP:benzo(a)pyrene} = (HV_{CA:benzo(a)pyrene} + HV_{NC:benzo(a)pyrene}) \text{ x } Amt_{TCoutput:benzo(a)pyrene}$$

Table 3-8 presents toxicity data for the example chemicals from Appendix K, Table K-8. Using benzo(a)pyrene as an example, the hazard values are calculated as follows:

Table 3-8. Toxicity data used in example calculations

Chemical	Cancer		Chronic noncancer effects	
	Weight of evidence	Slope factor (SF) (mg/kg-day)$^{-1}$	Oral (mg/kg-day)	Inhalation (mg/m^3)
Toluene	D, 3	none	100[b]	411.1[b]
Benzo(a)pyrene	B2, 2A	3.1[a] 7.3[c]	no data	no data

[a] inhalation SF
[b] NOAEL
[c] oral SF

Cancer effects:

$$\textit{oral}: \quad (HV_{CA_{oral}})_i = \frac{oral\ SF_i}{oral\ SF_{mean}}$$

$HV_{CAoral:benzo(a)pyrene}$ $= 7.3\ (mg/kg\text{-}day)^{-1} \div 0.71\ (mg/kg\text{-}day)^{-1}$
$= 10.3$

$$\textit{inhalation}: \quad (HV_{CA_{inh}})_i = \frac{inhalation\ SF_i}{inhalation\ SF_{mean}}$$

$HV_{CAinhalation:benzo(a)pyrene}$ $= 3.1\ (mg/kg\text{-}day)^{-1} \div 1.7\ (mg/kg\text{-}day)^{-1}$
$= 1.82$

Thus, the cancer HV is 10.3, the greater of the two values.

Noncancer effects:

Since no data are available for noncancer effects, a default HV of one is assigned, representative of mean toxicity.

Total HV:

Thus the total hazard value for benzo(a)pyrene is given by:

$HV_{benzo(a)pyrene}$ $= HV_{CA} + HV_{NC}$
$= 10.3 + 1$
$= 11.3$

Similarly, the HV for toluene is found to be 0.12. Given the following hypothetical output amounts:

$Amt_{TC\text{-}O:TOLUENE}$ = 1.3 kg of toluene per functional unit
$Amt_{TC\text{-}O:BENZO(A)PYRENE}$ = 0.1 kg of benzo(a)pyrene per functional unit

the resulting impact scores are as follows:

$IS_{CHP\text{-}W:TOLUENE}$ = 0.12 x 1.3 = 0.16 tox-kg of toluene per functional unit
$IS_{CHP\text{-}W:BENZO(A)PYRENE}$ = 11.3 x 0.1 = 1.13 tox-kg of benzo(a)pyrene per functional unit

If these were the only outputs from Process A relevant to chronic public health effects, the total impact score for this impact category for Process A would be:

$$
\begin{aligned}
IS_{CHP:PROCESS\_A} &= IS_{CHP\text{-}W:TOLUENE} + IS_{CHP\text{-}W:BENZO(A)PYRENE} \\
&= 0.16 + 1.13 \\
&= 1.29 \text{ tox-kg per functional unit for Process A.}
\end{aligned}
$$

If the product system Y contained three processes altogether (Processes A, B, and C), and the impact scores for Process B and C were 2.5 and 3.0, respectively, impact scores would be added together to yield a total impact score for the product system relevant to chronic public health effects:

$$
\begin{aligned}
IS_{CHP:PROFILE\_Y} &= IS_{CHP:PROCESS\_A} + IS_{CHP:PROCESS\_B} + IS_{CHP:PROCESS\_C} \\
&= 1.29 + 2.5 + 3.0 \\
&= 6.8 \text{ tox-kg per functional unit for Profile Y.}
\end{aligned}
$$

An environmental profile would then be the sum of all the processes within that profile for each impact category.

3.1.3 Data Sources and Data Quality

Data that are used to calculate impacts are from: (1) equivalency factors or parameters used to identify hazard values; and (2) LCI items. Equivalency factors and data used to develop hazard values, which have been presented in this methodology, include GWP, ODP, POCP, AP, EP, WOE, SF, mammalian LOAEL/NOAEL, OTV, fish LC_{50}, and fish NOAEL. Published lists of the chemical-specific parameter values exist for GWP, ODP, POCP, AP, EP and OTV (see Appendix K). The other parameters may exist for a large number of chemicals and several data sources must be searched to identify the appropriate parameter values. Priority is given to peer-reviewed databases (e.g., HEAST, IRIS, HSDB), then other databases (e.g., RTECS), other studies or literature, and finally estimation methods [e.g., structure-activity relationships (SARs) or quantitative structure-activity relationships (QSARs)]. The specific toxicity data that are used in the CDP are presented in Appendix K, Table K-8. The sources of each parameter presented in this report, and the basis for their values, are presented in Table 3-9. Data quality is affected by the type of data source (e.g., primary versus secondary data), the currency of the data, and the accuracy and precision of the data, and will depend on the source. The sources and quality of the LCI data used to calculate impact scores were discussed in Chapter 2. Data sources and data quality for each impact category are discussed further in Section 3.3, Baseline LCIA Results.

3.1.4 Limitations and Uncertainties

This section summarizes some of the limitations and uncertainties in LCIA methodology, in general. Specific limitations and uncertainties in each impact category are discussed in Section 3.3 with the baseline LCIA results.

The purpose of an LCIA is to evaluate the *relative potential* impacts of a product system for various impact categories. There is no intent to measure the *actual* impacts or provide spatial or temporal relationships linking the inventory to specific impacts. The LCIA is intended to provide a screening-level evaluation of impacts. More detailed characterization of exposure and toxicity has been conducted on selected materials for the CDP in Chapter 4.

Table 3-9. Data sources for equivalency factors and hazard values

Parameter	Basis of Parameter Values	Source
Global warming potential (GWP)	atmospheric lifetimes and radiative forcing compared to CO_2	Houghton *et al.*, 1996
Ozone depletion potential (ODP)	the change in the ozone column in the equilibrium state of a substance compared to CFC-11	Heijungs *et al.*, 1992; CAAA, 1990
Photochemical oxidant creation potential (POCP)	simulated trajectories of ozone production with and without VOCs present compared to ethene	Heijungs *et al.*, 1992
Acidification potential (AP)	number of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released compared to SO_2	Heijungs *et al.*, 1992; Hauschild and Wenzel, 1997
Nutrient enrichment/eutrophication potential (EP)	ratio of N to P in the average composition of algae ($C_{106}H_{263}O_{110}N_{16}P$) compared to phosphate (PO_4^{3-})	Heijungs *et al.*, 1992; Lindfors *et al.*, 1995
Weight-of-evidence (WOE)	classification of carcinogenicity by EPA or IARC based on human and/or animal toxicity data	EPA, 1999; IARC, 1998
Slope factor (SF)	measure of an individual's excess risk or increased likelihood of developing cancer if exposed to a chemical, based on dose-response data	IRIS and HEAST as cited in Risk Assessment Information System (RAIS) online database
Mammalian: Lowest observed adverse effect level / No observed adverse effect level (LOAEL/NOAEL)	mammalian (primarily rodent) toxicity studies	IRIS, HEAST and various literature sources provided by EPA contractor
Fish lethal concentration to 50% of the exposed population (LC_{50})	fish (primarily fathead minnow) toxicity studies	Various literature sources and Ecotox database
Fish NOAEL	fish (primarily fathead minnow) toxicity studies	Literature sources and Ecotox database
Odor threshold value (OTV)	measured odor thresholds in humans	EPA, 1992

In addition to lacking temporal or spatial relationships and providing only relative impacts, LCA is also limited by the availability and quality of the inventory data. Data collection can be very time consuming and expensive. Confidentiality issues may also inhibit the availability of primary data.

Uncertainties are inherent in each parameter described in Table 3-9 and the reader is referred to each source for more information on associated uncertainties. For example, toxicity data require extrapolations from animals to humans and from high to low doses (for chronic effects) and can have a high degree of uncertainty.

Uncertainties also are inherent in chemical ranking and scoring systems, such as the scoring of inherent properties approach used for human health and ecotoxicity effects. In particular, systems that do not consider the fate and transport of chemicals in the environment can contribute to misclassifications of chemicals with respect to risk. Also, uncertainty is introduced where it was assumed that all chronic endpoints are equivalent, which is likely not the case. In addition, when LOAELs were not available but NOAELs were, a factor of ten was applied to the NOAEL to estimate the LOAEL, introducing uncertainty. The human health and ecotoxicity impact characterization methods presented here are screening tools that cannot substitute for more detailed risk characterization methods. However, it should be noted that in LCA, chemical toxicity is often not considered at all. This methodology is an attempt to consider chemical toxicity where it is often ignored.

Uncertainty in the inventory data depends on the responses to the data collection questionnaires and other limitations identified during inventory data collection. These uncertainties are carried into impact assessment. In this LCA, there was uncertainty in the inventory data, which included but was not limited to the following:

- missing individual inventory items,
- missing processes or sets of data,
- measurement uncertainty,
- estimation uncertainty,
- allocation uncertainty/working with aggregated data, and
- unspeciated chemical data.

The goal definition and scoping process helped reduce the uncertainty from missing data, although it is certain that some (missing data) still exist. As far as possible, the remaining uncertainties were reduced primarily through quality assurance/quality control measures (e.g., performing systematic double-checks of all calculations on manipulated data). The limitations and uncertainties in the inventory data were discussed further in Chapter 2.

3.2 DATA MANAGEMENT AND ANALYSIS SOFTWARE

The inventory and chemical characteristics data for the CDP are stored in a database within a software package developed by UT, using the Microsoft Visual FoxPro application programming language, under a cooperative agreement with the EPA Office of Research and Development. The software package calculates impact scores based on the stored inventory and chemical data and on the appropriate formulas for each impact category, as presented in Section 3.1.

3.3 BASELINE LCIA RESULTS

This section presents the baseline LCIA results calculated using the impact assessment methodology presented in Section 3.1. As noted in the section on baseline LCI results (Section 2.7.1), the baseline scenario meets the following conditions:

- uses the effective life use stage scenario (e.g., use stage calculations are based on the actual amount of time a monitor is used by one or multiple users before it reaches its final disposition);
- uses the average value of all the energy inputs from the primary data for glass manufacturing;
- removes two outliers from the primary data for energy inputs during LCD panel/module manufacturing and then uses the average of the remaining energy inputs;
- excludes transportation in the manufacturing stage, but includes any transportation embedded in upstream data sets;
- includes the manufacturing processes of materials used as fuels (e.g., natural gas, fuel oil) in the manufacturing stage instead of in the upstream, materials processing stage. In cases where materials normally considered to be fuels are used as ancillary materials, their manufacturing processes are included with other upstream processes; and
- assumes LCD glass manufacturing processes use the same amounts of energy as CRT glass manufacturing per kilogram of glass produced.

Section 3.3.1 summarizes the baseline life cycle impact category indicators for both the CRT and LCD. Sections 3.3.2 through 3.3.14 present a breakdown of the impact category indicators by life-cycle stage, list the materials that contribute 99% of the total for both monitor types, and discuss limitations and uncertainties in each impact category. Each of the tables in this report shows the top contributors to the impacts because the complete tables, which are provided in Appendix J, are often lengthy. Section 3.3.15 summarizes the top contributors to each impact category, and Appendix M presents complete LCIA results.

3.3.1 Summary of Baseline LCIA Results

Table 3-10 presents the baseline CRT and LCD LCIA indicator results for each impact category, calculated using the impact assessment methodology presented in Section 3.1. The indicator results presented in the table are the result of the characterization step of LCIA methodology where LCI results are converted to common units and aggregated within an impact category. Note that the impact category indicator results are in a number of different units and therefore can not be summed or compared across impact categories. Note also that the CDP LCIA methodology does not perform the optional LCIA steps of normalization (calculating the magnitude of category indicator results relative to a reference value), grouping (sorting and possibly ranking of indicators), or weighting (converting and possibly aggregating indicator results across impact categories). Ranking and weighting, in particular, are subjective steps that depend on the values of the different individuals, organizations, or societies performing the analysis. Since the CDP involves a variety of stakeholders from different geographic regions and with different values, these more subjective steps were intentionally excluded from the CDP LCIA methodology.

Table 3-10. Baseline life-cycle impact category indicators[a]

Impact category	Units per monitor	CRT	LCD
Renewable resource use	kg	**1.31E+04**	2.80E+03
Nonrenewable resource use	kg	**6.68E+02**	3.64E+02
Energy use	MJ	**2.08E+04**	2.84E+03
Solid waste landfill use	m^3	**1.67E-01**	5.43E-02
Hazardous waste landfill use	m^3	**1.68E-02**	3.61E-03
Radioactive waste landfill use	m^3	**1.81E-04**	9.22E-05
Global warming	kg-CO_2 equivalents	**6.95E+02**	5.93E+02
Ozone depletion	kg-CFC-11 equivalents	2.05E-05[b,c]	1.37E-05[b]
Photochemical smog	kg-ethene equivalents	**1.71E-01**	1.41E-01
Acidification	kg-SO_2 equivalents	**5.25E+00**	2.96E+00
Air particulates	kg	**3.01E-01**	1.15E-01
Water eutrophication	kg-phosphate equivalents	4.82E-02	**4.96E-02**
Water quality, BOD	kg	**1.95E-01**	2.83E-02
Water quality, TSS	kg	**8.74E-01**	6.15E-02
Radioactivity	Bq	**3.85E+07**[d]	1.22E+07[d]
Chronic health effects, occupational	tox-kg	**9.34E+02**	6.96E+02
Chronic health effects, public	tox-kg	**1.98E+03**	9.02E+02
Aesthetics (odor)	m^3	**7.58E+06**	5.04E+06
Aquatic toxicity	tox-kg	2.25E-01	**5.19E+00**
Terrestrial toxicity	tox-kg	**1.97E+03**	8.94E+02

[a] Bold indicates the larger value within an impact category when comparing the CRT and LCD.

[b] Several of the substances included in this category were phased out of production by January 1, 1996. Excluding phased out substances decreases the CRT ozone depletion indicator to 1.09E-05 kg CFC-11 equivalents per monitor and the LCD ozone depletion indicator to 1.18E-05 kg CFC-11 equivalents per monitor. These ozone depletion indicators are probably more representative of the CDP temporal boundaries and current operating practices. See Section 3.3.6 for details.

[c] Although the CRT indicator appears larger than the LCD indicator, uncertainties in the inventory make it difficult to determine which monitor has the greater value. Therefore, this value is not shown in bold.

[d] Radioactivity impacts are being driven by radioactive releases from nuclear fuel reprocessing in France, which are included in the electricity data in some of the upstream, materials processing data sets. See Section 3.3.12 for details.

As shown in the table, under the baseline conditions the CRT indicators are greater than the LCD indicators in the following categories: renewable resource use, nonrenewable resource use, energy use, solid waste landfill use, hazardous waste landfill use, radioactive waste landfill use, global warming, photochemical smog, acidification, air particulates, biological oxygen demand (BOD), total suspended solids (TSS), radioactivity, chronic public health effects, chronic occupational health effects, aesthetics, and terrestrial toxicity. The LCD indicators are greater than the CRT indicators in the following categories: water eutrophication and aquatic toxicity. In addition, as noted in Table 3-10, the CRT ozone depletion indicator is greater than that of the LCD when phased out substances are left in the CRT and LCD inventories. However, if phased out substances are removed from the CRT and LCD inventories, the LCD ozone depletion indicator would exceed that of the CRT.

A number of the impact results for both monitor types, and for the CRT in particular, are being driven by a few data points with relatively high uncertainty. Therefore, sensitivity analyses of the baseline results are presented in Section 3.4.

3.3.2 Renewable and Nonrenewable Resource Use

3.3.2.1 Renewable resource use

Figure 3-2 presents the CRT and LCD impact category indicators for renewable resource use by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.1. Tables M-1 and M-2 in Appendix M present complete renewable resource results for the CRT and LCD, respectively. A renewable resource is one that is being replenished at a rate greater than or equal to its rate of depletion. Note that several of the resources listed in the Appendix and in the tables that follow are not renewable or can not be replenished, *per se*, but are considered renewable since they can be restored or are present in nearly infinite, non-depletable amounts. For example, water is typically considered a renewable resource since it can be restored to potable quality and is therefore being "replenished" at a rate greater than or equal to its rate of depletion. However, current trends toward shortages of potable water suggest that water might be more appropriately classified as a nonrenewable resource.

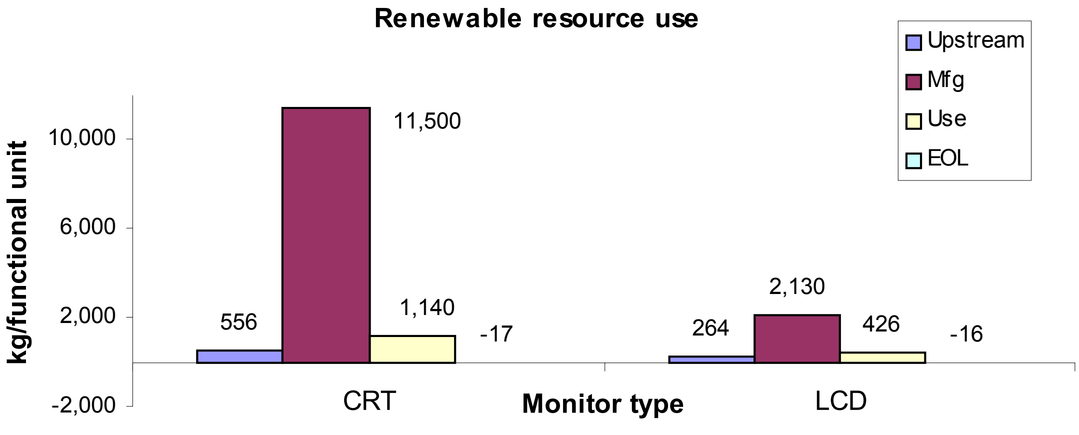

Figure 3-2. Renewable resource use impacts by life-cycle stage

As shown in Figure 3-2, the baseline life-cycle impact category indicator for renewable resource use is 13,100 kg per monitor for the CRT and 2,800 kg per monitor for the LCD. Both the CRT and LCD renewable resource use results are dominated by the manufacturing life-cycle stage, with manufacturing accounting for 87% and 76% of the CRT and LCD totals, respectively.

Table 3-11 presents the life-cycle inventory items that contribute to the top 99% of the CRT renewable resource use total. It also lists the LCI data type (primary, secondary, or model/secondary). As shown in Table 3-11, water used in the production of LPG clearly dominates the CRT renewable resource use impact score. LPG is primarily used as an energy source in CRT glass manufacturing, indicating that the glass/frit process group is ultimately the greatest contributor to the CRT renewable resource use impact score. Other significant contributors include water used to produce electricity in the United States during the use of the monitor, water used in CRT tube manufacturing, and water used in the production of steel. The LCI data for LPG production and steel manufacturing are from secondary sources, while the LCI data for the U.S. electric grid are based on the model developed by the CDP for the amount of electricity consumed by a CRT during use combined with data from secondary sources on the inputs and outputs from U.S. power plants. CRT tube manufacturing LCI data are primary data collected by the CDP.

Table 3-11. Top 99% of the CRT renewable resource use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	Water	Secondary	79%
Use	U.S. electric grid	Water	Model/secondary	8.7%
Manufacturing	CRT tube manufacturing	Water	Primary	6.2%
Materials processing	Steel production, cold-rolled, semi-finished	Water	Secondary	3.6%
Manufacturing	Japanese electric grid	Water	Model/secondary	0.34%
Manufacturing	PWB manufacturing	Water	Primary	0.32%

* Column may not add to 99% due to rounding.

Table 3-12 presents the inventory items contributing to the top 99% of the LCD renewable resource use total and the LCI data types (primary, secondary, or model/secondary). As shown in the table, water used in LCD module/monitor manufacturing is the greatest contributor to the LCD renewable resource use impact score. Other significant contributors include water used in the production of LPG, water used by the U.S. electric grid during the use life-cycle stage, and water used in steel production. It is LCD glass manufacturing that consumes the LPG responsible for the high LCD renewable resource use score. The LCI data for LCD module manufacturing are primary data collected by the CDP. LPG production and steel manufacturing are from secondary sources, while the LCI data for the U.S electric grid are based on the model developed by the CDP for the amount of electricity consumed by an LCD during the use stage combined with data from secondary sources.

Table 3-12. Top 99% of the LCD renewable resource use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LCD module/monitor mfg.	Water	Primary	38%
Manufacturing	LPG production	Water	Secondary	18%
Use	U.S. electric grid	Water	Model/secondary	15%
Materials processing	Steel production (cold-rolled, semi-finished)	Water	Secondary	8.2%
Manufacturing	LCD panel components	Water	Primary	6.4%
Manufacturing	Backlight	Water	Primary	6.8%
Manufacturing	Japanese electric grid	Water	Model/secondary	5.3%
Manufacturing	PWB Manufacturing	Water	Primary	0.66%

* Column may not add to 99% due to rounding.

3.3.2.2 Nonrenewable resource use

Figure 3-3 presents the CRT and LCD impact category indicators for nonrenewable resource use by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.1. Tables M-3 and M-4 in Appendix M present complete nonrenewable resource results for the CRT and LCD, respectively. The total nonrenewable resource use indicator was 668 kg per monitor for the CRT and 364 kg per monitor for the LCD. As shown in Figure 3-3, the CRT nonrenewable resource use results are dominated by the manufacturing life-cycle stage, which contributed 68% of the total. The LCD nonrenewable resource use score is dominated by the upstream materials processing stages, which contributed 69% of the total.

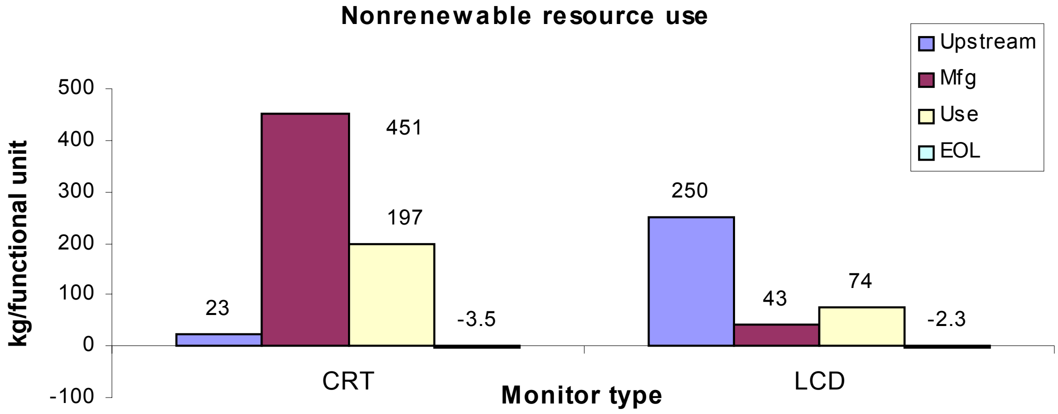

Figure 3-3. Nonrenewable resource use impacts by life-cycle stage

Table 3-13 presents the inventory items contributing to the top 99% of the CRT nonrenewable resource use impact score. It also lists the LCI data type (primary, secondary, or model/secondary). Similar to the renewable resource use LCIA results, the LPG production process, which mainly supports the CRT glass manufacturing process, clearly dominates the CRT nonrenewable resource use impact score. Petroleum used to make LPG is the non-renewable resource being consumed by the LPG production process in the greatest amounts, followed by natural gas, and coal. Note that the LPG actually consumed during CRT glass manufacturing does not appear in the nonrenewable resource use results. This is because it was accounted for in the nonrenewable resource use score for the LPG production process when it was extracted from the ground.

Fuels (coal and natural gas) consumed by the U.S. electric grid during monitor use are also among the greatest contributors to the CRT nonrenewable resource use impact scores. The LCI data for LPG production are from secondary sources, while the LCI data for the U.S. electric grid are based on the model developed by the CDP for the amount of electricity consumed by a CRT during use combined with data from secondary sources on the inputs and outputs from U.S. power plants.

Table 3-13. Top 99% of the CRT nonrenewable resource use impact score

Life-cycle stage	Process group	Material*	LCI data type	Contribution to impact score*
Manufacturing	LPG production	Petroleum (in ground)	Secondary	56%
Use	U.S. electric grid	Coal, average (in ground)	Model/secondary	27%
Manufacturing	LPG production	Natural gas (in ground)	Secondary	6.7%
Use	U.S. electric grid	Natural gas	Model/secondary	2.1%
Manufacturing	LPG production	Coal, average (in ground)	Secondary	2.0%
Materials processing	Steel production, cold-rolled, semi-finished	Iron Ore	Secondary	0.99%
Materials processing	Steel production, cold-rolled, semi-finished	Coal, average (in ground)	Secondary	0.60%
Manufacturing	Fuel oil #6 production	Petroleum (in ground)	Secondary	0.58%
Use	U.S. electric grid	Petroleum (in ground)	Model/secondary	0.57%
Manufacturing	Natural gas production	Natural gas (in ground)	Secondary	0.51%
Manufacturing	U.S. electric grid	Coal, average (in ground)	Model/secondary	0.43%
Manufacturing	Japanese electric grid	Coal, average (in ground)	Model/secondary	0.34%
Materials processing	Aluminum production	Bauxite	Secondary	0.20%
Manufacturing	Japanese electric grid	Petroleum (in ground)	Model/secondary	0.19%
Materials processing	Polycarbonate production	Natural gas (in ground)	Secondary	0.19%
Manufacturing	Japanese electric grid	Natural gas	Model/secondary	0.19%

* Column may not add to 99% due to rounding.

Table 3-14 presents the inventory items contributing to the top 99% of the LCD non-renewable resource use impact score. In this case, the impact score is dominated by the natural gas extracted to produce natural gas in the upstream, materials processing life-cycle stage. Liquified natural gas (LNG) from this production process is used as an ancillary material in the LCD module/monitor manufacturing process group, indicating LCD module/monitor manufacturing is ultimately responsible for this non-renewable resource use. However, only one of the seven companies that provided data for the LCD module/monitor manufacturing process group reported this use of LNG. Note that the actual use of LNG in the LCD module/manufacturing process group does not appear in the nonrenewable resource results. Similar to the LPG results discussed above for the CRT, this is because it has been accounted for in the natural gas production process results.

Other primary contributors to this impact score include coal used to produce electricity for the U.S. electric grid, and petroleum used to produce LPG. The LCI data for all of the primary contributors to the LCD non-renewable resource use score were either from secondary sources or CDP models combined with secondary sources.

Table 3-14. Top 99% of the LCD nonrenewable resource use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Natural gas production	Natural gas (in ground)	Secondary	65%
Use	U.S. electric grid	Coal, average (in ground)	Model/secondary	18%
Manufacturing	LPG production	Petroleum (in ground)	Secondary	4.9%
Manufacturing	Japanese electric grid	Coal, average (in ground)	Model/secondary	2.1%
Manufacturing	Natural gas production	Natural gas (in ground)	Secondary	1.5%
Use	U.S. electric grid	Natural gas	Model/secondary	1.4%
Manufacturing	Japanese electric grid	Petroleum (in ground)	Model/secondary	1.2%
Manufacturing	Japanese electric grid	Natural gas	Model/secondary	1.2%
Materials processing	Steel production (cold-rolled, semi-finished)	Iron ore	Secondary	0.89%
Manufacturing	LPG production	Natural gas (in ground)	Secondary	0.59%
Materials processing	Steel production (cold-rolled, semi-finished)	Coal (in ground)	Secondary	0.54%
Materials processing	Natural gas production	Coal (in ground)	Secondary	0.45%
Use	U.S. electric grid	Petroleum (in ground)	Model/secondary	0.39%

*Column may not add to 99% due to rounding

3.3.2.3 Limitations and uncertainties

The renewable and nonrenewable resource use results presented here are based on the mass of a material consumed. Depletion of renewable materials, which results from the extraction of renewable resources faster than they are renewed, may occur but is not specifically modeled or identified in the renewable resource impact scores. This may be particularly important for water, which, while considered a renewable resource, is in shorter and shorter supply as world population grows and more of the world's water resources become degraded. For the nonrenewable materials use category, depletion of materials results from the extraction of nonrenewable resources. However, the impact scores do not directly relate consumption rates to the earth's ability to sustain that consumption.

The CRT and LCD impact scores for renewable resource use, and the CRT impact score for nonrenewable resources use, are being driven by the fuels consumed during CRT or LCD glass manufacturing. However, as discussed in Section 2.3.3.3, there is a high degree of variability in the three sets of CRT glass manufacturing energy data received by the CDP. Furthermore, as discussed in Section 2.3.3.1, LCD glass manufacturing data were developed from the CRT data because no companies were willing to supply the LCD data. Therefore, glass energy use inputs are uncertain for both the CRT and the LCD and were the subject of a sensitivity analysis, discussed in Section 3.4.

The LCD impact score for nonrenewable resource use is being driven by LNG used as an ancillary material during LCD module/monitor manufacturing. However, only one LCD module/monitor manufacturer reported using LNG as an ancillary material, which was confirmed by CDP researchers in follow-up communications. Given the fact that only one of seven manufacturers reported the ancillary use of LNG, the LCD nonrenewable resource use indicator may not be representative of the industry as a whole. If we remove this application of LNG from the LCD inventory, the LCD nonrenewable resource result is reduced by 66%, from 364 kg per monitor to 125 kg per monitor.

Inventory data for most of the materials contributing 99% of the CRT and LCD impact scores come from secondary sources, and were not developed specifically for the CDP. The limitations and uncertainties associated with secondary data sources are summarized in Section 2.2.2. Table 3-15 looks more closely at the LPG and natural gas production geographic and temporal boundaries. These are the production processes that are driving a large part of the CRT and LCD resources use indicators. As shown in the table, most of the LPG and natural gas production data are for the United States, although the LPG data set includes some data from other countries. Both data sets rely on several different sources and have different temporal boundaries. In particular, LPG production data are less recent, and may not accurately reflect current production practices. All of these factors create some inconsistencies among the data sets and reduce the data quality when used for the purposes of the CDP. However, this is a common difficulty with LCA, which often uses data from secondary sources to avoid the tremendous amount of time and resources required to collect all the needed data.

Table 3-15. LPG and natural gas production geographic and temporal boundaries

Production Process	Location	Source	Year
LPG production	Mainly U.S., but includes some other countries	Seven sources cited	1983 to 1993
Natural gas production	U.S.	Six sources cited	1987 to 1998

3.3.3 Energy Use

Figure 3-4 presents the CRT and LCD impact results for energy use by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.2. Tables M-5 and M-6 in Appendix M list complete energy use results for the CRT and LCD, respectively. The total indicator for this impact category was 20,800 MJ per monitor for the CRT, and 2,840 MJ per monitor for the LCD.

CRTs generally are assumed to have greater life-cycle energy use impacts than the LCDs due to the high energy requirements in the use stage. This is borne out by the results in Figure 3-4, which show that CRT energy consumption during use is roughly 2.7 times that of the LCD. However, contrary to expectations, CRT energy use impacts are driven by the manufacturing life-cycle stage, which contributes about 88% of the total score. The use stage, which was expected to be responsible for a large amount of energy consumption impacts, only contributes about 11% of the total score. LCD energy consumption impacts are also largest in the manufacturing life-cycle stage which accounts for almost 51% of the impacts in this category. Both the use and upstream (materials processing) life-cycle stages are also significant contributors to LCD life-cycle energy use, accounting for 30 and 22%, respectively. Note that the sum of the upstream, manufacturing, and use life-cycle stages is greater than 100% due to an energy credit for incineration with energy recovery at the end of a monitor's useful life.

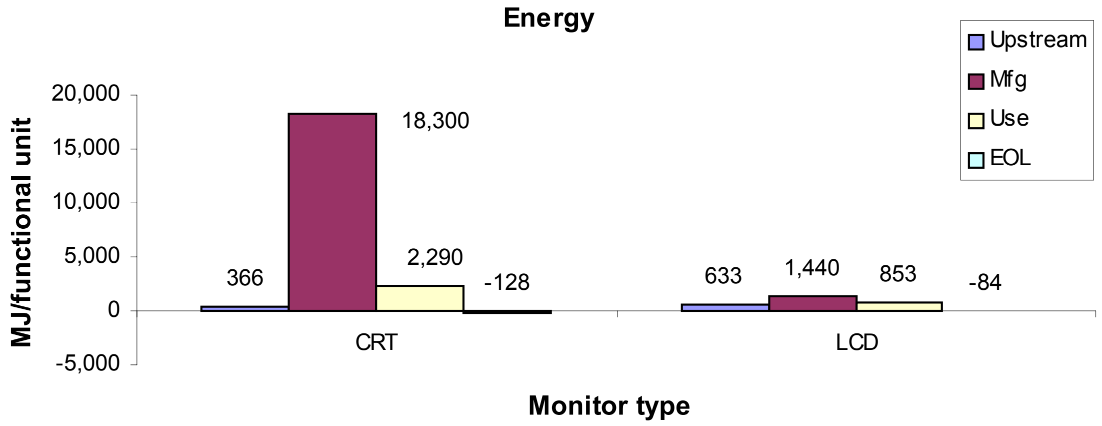

Figure 3-4. Energy impacts by life-cycle stage

3.3.3.1 Major contributors to the CRT energy use results

Table 3-16 presents the life-cycle inventory items contributing to the top 99% of the CRT energy use results and the LCI data type (primary, secondary, or model/secondary). As shown in the table, LPG used in the glass/frit process group, primarily from CRT glass manufacturing, clearly dominates the CRT energy use result, followed by electricity consumed during use of a CRT monitor, and natural gas, petroleum, and coal consumed during LPG production. Since LPG is used primarily as an energy source during CRT glass manufacturing, most of the sum of the glass/frit manufacturing and LPG production energy use impacts—roughly 87% of the CRT life-cycle energy use impacts—can be attributed to the CRT glass manufacturing process.

Table 3-16. Top 99% of the CRT energy use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	Glass/frit manufacturing	Liquified petroleum gas	Primary	72%
Use	CRT monitor use	Electricity	Model/secondary	11%
Manufacturing	LPG production	Natural gas (in ground)	Secondary	10%
Manufacturing	LPG production	Petroleum (in ground)	Secondary	2.0%
Manufacturing	LPG production	Coal, average (in ground)	Secondary	1.4%
Manufacturing	CRT tube manufacturing	Fuel oil #6	Primary	0.72%
Manufacturing	Glass/frit manufacturing	Natural gas	Primary	0.26%
Manufacturing	Glass/frit manufacturing	Fuel oil # 2	Primary	0.24%
Manufacturing	Glass/frit manufacturing	Electricity	Primary	0.23%
Manufacturing	CRT tube manufacturing	Natural gas	Primary	0.18%
Materials processing	Polycarbonate production	Natural gas (in ground)	Secondary	0.16%
Manufacturing	LPG production	Uranium (U, ore)	Secondary	0.16%
Manufacturing	CRT tube manufacturing	Electricity	Primary	0.15%
Manufacturing	Glass/frit manufacturing	Electricity	Primary	0.13%

*Column may not add to 99% due to rounding.

3.3.3.2 Major contributors to the LCD energy use results

Table 3-17 lists the inventory items contributing to the top 99% of the LCD life-cycle energy use results. Electricity consumed during use of the LCD monitor by the consumer is the single largest contributor to LCD energy use impacts, closely followed by LPG utilized to produce LCD glass. Other major contributors include natural gas consumed during natural gas production, electricity and LNG used as a fuel during LCD monitor/module manufacturing, and natural gas consumed during LPG production. Note that the LNG used as an ancillary material in LCD module/monitor manufacturing is not included in the LCD energy use impact calculations since it is not used as a source of energy. However, natural gas used as an energy source to produce the LNG is included (the third item listed in the table).

Table 3-17. Top 99% of the LCD energy use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	LCD monitor use	Electricity	Model/ secondary	30%
Manufacturing	LCD glass manufacturing	Liquified petroleum gas	Primary	25%
Materials processing	Natural gas production	Natural gas (in ground)	Secondary	14%
Manufacturing	LCD module/monitor mfg.	Electricity	Primary	8.9%
Manufacturing	LCD module/monitor mfg.	Liquified natural gas	Primary	5.8%
Manufacturing	LPG production	Natural gas (in ground)	Secondary	3.4%
Manufacturing	LCD panel components	Electricity	Primary	1.4%
Manufacturing	LCD module/monitor mfg.	Natural gas	Primary	1.3%
Materials processing	Natural gas production	Coal (in ground)	Secondary	1.3%
Materials processing	Natural gas production	Petroleum (in ground)	Secondary	0.89%
Manufacturing	LCD module/monitor mfg.	Liquified petroleum gas	Primary	0.88%
Manufacturing	LPG production	Petroleum (in ground)	Secondary	0.69%
Materials processing	Polycarbonate production	Natural gas (in ground)	Secondary	0.67%
Manufacturing	LPG production	Coal (in ground)	Secondary	0.51%
Manufacturing	LCD module/monitor mfg.	Kerosene	Primary	0.46%
Materials processing	PMMA sheet production	Petroleum (in ground)	Secondary	0.42%
Materials processing	PMMA sheet production	Natural gas (in ground)	Secondary	0.41%
Materials processing	Steel production (cold-rolled, semi-finished)	Petroleum (in ground)	Secondary	0.36%
Materials processing	Steel production (cold-rolled, semi-finished)	Natural gas (in ground)	Secondary	0.35%
Manufacturing	Natural gas production	Natural gas (in ground)	Secondary	0.32%
Materials processing	PMMA sheet production	Electricity	Secondary	0.32%
Materials processing	Steel production (cold-rolled, semi-finished)	Electricity	Secondary	0.31%
Manufacturing	LCD module/monitor mfg.	Fuel oil # 4	Primary	0.31%
Materials processing	Styrene-butadiene copolymer production	Natural gas (in ground)	Secondary	0.29%
Materials processing	Aluminum production	Coal (in ground)	Secondary	0.29%

*Column may not add to 99% due to rounding.

3.3.3.3 Limitations and uncertainties

Some of the limitations and uncertainties in the energy use indicators are similar to those in the renewable and nonrenewable resource use categories. First, as discussed in Section 3.3.1.1, the energy data for both CRT and LCD glass manufacturing are uncertain due to the variability in the primary glass data received by the CDP from three glass manufacturers. Glass manufacturing energy data are the subject of a sensitivity analysis in Section 3.4. Second, data for LPG production and natural gas production, which are among the largest contributors to the energy use indicators, are from secondary sources and are therefore subject to the limitations and uncertainties associated with secondary data (see Section 2.2.2 and 3.3.1.1). Not counting the use stage data, note that about 14% of the CRT energy use impacts shown in Table 3-16, above, are from secondary sources, compared to about 24% of the LCD energy use impacts (Table 3-17).

The amount of electricity consumed during use of a monitor was modeled by the CDP from secondary sources on the amount of electricity consumed during different power modes and the amount of time a monitor spends in each mode. Data quality for the effective life scenario (the baseline scenario presented here) is considered to be excellent, based on the source and quality information detailed in Appendix H and discussed in Sections 2.4.2 and 2.4.3.

3.3.4 Landfill Use

3.3.4.1 Solid waste landfill use

Figure 3-5 presents the CRT and LCD LCIA results for the solid waste landfill use impact category, based on the impact assessment methodology presented in Section 3.1.2.3. Tables M-7 and M-8 in Appendix M present complete results for the CRT and LCD, respectively. Life-cycle solid waste landfill use was 0.17 m^3 for the CRT and 0.054 m^3 for the LCD. The solid waste landfill indicators for both monitor types are dominated by waste disposal during the use stage—which contributes 59% of the total for the CRT and 68% for the LCD—primarily from wastes generated as a by-product of electricity production. Both monitor types have negative solid waste impact scores during the end-of-life stage. This is due to an energy credit from incineration processes, which offsets some of the solid waste impacts from electricity generation.

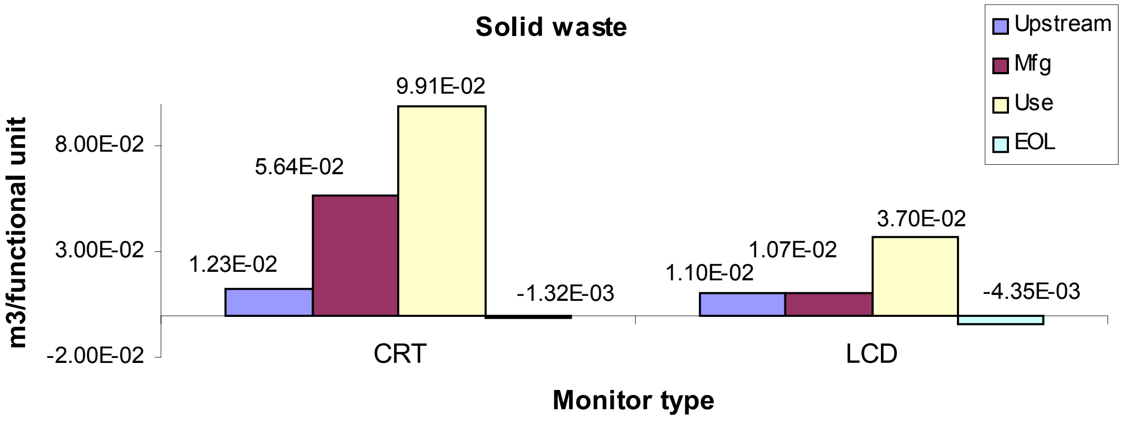

Figure 3-5. Solid waste impacts by life-cycle stage

Table 3-18 presents the materials that contribute to the top 99% of the CRT solid waste landfill use impact score. Note that the material contributions actually add to greater than 100% due to the energy credit from incineration processes, discussed above. Coal waste from U.S. electricity production is the single largest contributor to CRT impacts in this impact category, followed by slag and ash from LPG production, and dust/sludge and fly bottom ash from U.S.

electricity production. Electricity is used to power the monitor during the use stage, while LPG is primarily used in the production of CRT glass during manufacturing. LPG production also results in an unspecified solid waste that contributes 4.5% of the CRT solid waste impact score, while the CRT glass/frit process group generates a wastewater treatment sludge that contributes 5% of the score. Thus, the CRT glass/frit process group contributes about 30% of the CRT solid waste impact score, either directly (as a result of the glass manufacturing process itself) or indirectly (from LPG production). Other processes that are significant contributors include steel production and the landfilling of a CRT at the end of its effective life. The latter value is based on the assumption that 25% of CRTs that have reached their end of life are disposed of in a solid waste landfill (see Section 2.5 and Appendix I).

Table 3-18. Top 99% of the CRT solid waste landfill use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Coal waste	Model/secondary	38%
Manufacturing	LPG production	Slag and ash	Secondary	21%
Use	U.S. electric grid	Dust/sludge	Model/secondary	12%
Use	U.S. electric grid	Fly bottom ash	Model/secondary	10%
Materials processing	Steel production, cold-rolled, semi-finished	Unspecified solid waste	Secondary	6.6%
End-of-Life	CRT landfilling	EOL CRT monitor, landfilled	Primary	5.0%
Manufacturing	LPG production	Unspecified waste	Secondary	4.5%
Manufacturing	CRT glass/frit mfg.	Waste water treatment sludge	Primary	4.4%

*Column adds to greater than 100% due to a credit from incineration with energy recovery during the EOL life-cycle stage.

CRT glass manufacturing data were collected specifically for the CDP, while data for other process groups were either modeled by the CDP from secondary sources (e.g., U.S. electric grid data) or are entirely from secondary sources (e.g., LPG and steel production data). The mass and volume of CRT materials that are landfilled were developed for the CDP based on the mass reported in each inventory data set (collected as primary data) and the density of CRT materials assumed to be disposed of in a solid waste landfill. Note that the upstream inventories, which were derived from secondary sources (i.e., *Ecobilan*), include electricity generation within the materials manufacturing processes. These inventories do not include coal waste as an output, but list "slag and ash" as an output. The different inventories used in this project have varying nomenclature and some of the solid waste materials listed in the table may indeed overlap.

Table 3-19 presents the materials that contribute to the top 99% of the LCD solid waste landfill use results. Like the CRT solid waste results, the material contributions in the table are actually greater than 100% due to some negative values at end-of-life from an incinerator energy credit. Coal waste, dust/sludge, and fly/bottom ash from U.S. electricity during the use stage dominate the LCD solid waste impacts, contributing 68% of the impact score. Other significant contributors include the following: (1) an unspecified solid waste from producing steel used in the manufacture of the monitor, (2) slag and ash generated during the production of natural gas which is then used by one LCD module/monitor manufacturer as an ancillary material (LNG) during LCD module/monitor manufacture, (3) a wastewater treatment sludge from LCD module/monitor manufacturing, (4) coal waste from the generation of electricity in Japan during manufacturing, and (5) landfilling of non-hazardous or non-recovered components of the LCD at the end of its effective life. The latter value is based on the assumption that 50% of LCDs are sent to a solid waste landfill at the end of their effective lives.

Table 3-19. Top 99% of the LCD solid waste landfill use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Coal waste	Model/secondary	44%
Use	U.S. electric grid	Dust/sludge	Model/secondary	13%
Use	U.S. electric grid	Fly/bottom ash	Model/secondary	11%
Materials processing	Steel production, cold-rolled, semi-finished	Unspecified solid waste	Secondary	9.9%
Materials processing	Natural gas production	Slag and ash	Secondary	7.7%
Manufacturing	LCD monitor/module mfg.	Waste water treatment sludge	Primary	5.6%
Manufacturing	Japanese electric grid	Coal waste	Model/secondary	5.0%
End-of-Life	LCD landfilling	EOL LCD monitor, landfilled	Primary	3.5%

*Column adds to greater than 100% due to a credit from incineration with energy recovery during the EOL life-cycle stage.

LCI data for LCD monitor/module manufacturing were collected by the CDP, and LCD solid waste disposal volumes were estimated by the CDP based on the amounts and density of LCD materials assumed to be disposed of in a solid waste landfill. Like the CRT, data for other process groups either were modeled by the CDP from secondary data sources or came from secondary sources. As discussed above for the CRT, the materials processing inventories from secondary sources (i.e., *Ecobilan*) include electricity generation within the materials manufacturing processes. The different inventories used in this project have varying nomenclature and some of the solid waste materials listed in the table may indeed overlap.

3.3.4.2 Hazardous waste landfill use

Figure 3-6 presents the CRT and LCD LCIA results for the hazardous waste landfill use impact category, based on the impact assessment methodology presented in Section 3.1.2.3. Tables M-9 and M-10 (see Appendix M) present complete hazardous waste landfill use results for the CRT and LCD, respectively. Hazardous waste landfill use impacts are characterized from hazardous waste outputs with a disposition of landfill, which includes about 83% of the 9.46 kg of hazardous waste/functional unit generated by the CRT life cycle and about 27% of the 6.3 kg/functional unit generated by the LCD life cycle. This consumes approximately 0.017 m^3 of hazardous waste landfill space for the CRT and 0.036 m^3 for the LCD, based on the mass and densities of the various materials. The results for both monitor types are dominated by monitor disposal at the end of its effective life. Approximately 46% of CRTs and 5% of LCDs are assumed to be landfilled as hazardous waste (see Section 2.5 and Appendix I).

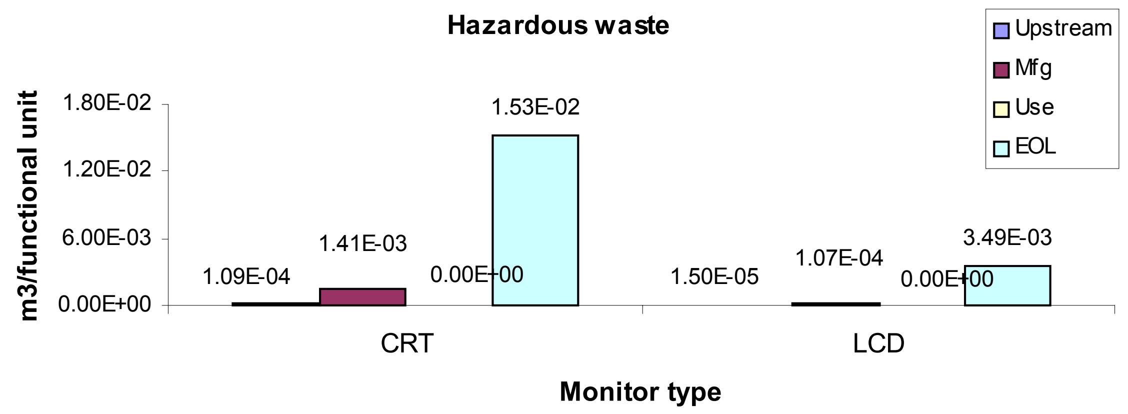

Figure 3-6. Hazardous waste impacts by life-cycle stage

Table 3-20 presents the materials that contribute to the top 99% of the CRT hazardous waste landfill use results. About 91% of the total hazardous waste landfill space consumed throughout the life-cycle of the CRT is from the amount of the monitor that is assumed to be disposed of as hazardous waste. The next largest contributor is an unspecified hazardous waste from LPG production. Most of this LPG is used to manufacture CRT glass. CRT outputs to a hazardous waste landfill at the end-of-life were estimated by the CDP. The LPG inventory is from secondary sources.

Table 3-20. Top 99% of the CRT hazardous waste landfill use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
End-of-Life	CRT landfilling	EOL CRT monitor, landfilled	Primary	91%
Manufacturing	LPG production	Hazardous waste	Secondary	8.1%

Table 3-21 lists the top contributors to the LCD hazardous waste landfill use results. LCD results are also dominated by landfilling of the LCD monitor at the end of its effective life, even though only 5% of LCDs are assumed to be landfilled. Other significant contributors include an unspecified hazardous waste from LPG production, and acetic acid from LCD monitor/module manufacturing. LPG is used in the manufacture of LCD glass. LCD outputs to a hazardous waste landfill at the end-of-life were estimated by the CDP. The LPG inventory is from secondary sources.

Table 3-21. Top 99% of the LCD hazardous waste landfill use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
End-of-Life	LCD landfilling	EOL LCD monitor, landfilled	Primary	97%
Manufacturing	LPG production	Hazardous waste	Secondary	1.8%
Manufacturing	LCD monitor/module mfg.	Acetic acid	Primary	0.88%

3.3.4.3 Radioactive waste landfill use

Figure 3-7 presents the CRT and LCD LCIA results for the radioactive waste landfill use impact category, based on the impact assessment methodology presented in Section 3.1.2.3. Tables M-11 and M-12 in Appendix M present complete results for the CRT and LCD, respectively. Life-cycle radioactive waste landfill use indicators for the CRT are 1.81E-04 m^3 per monitor for the CRT and 9.22E-05 m^3 per monitor for the LCD. As shown in the figure, CRT radioactive waste landfill impacts are dominated by radioactive waste disposal in the use stage, which contributes about 79% of the total impacts. This result is to be expected, given the relatively large amount of electricity consumed by a CRT during use and the associated radioactive waste from nuclear power plants. The use stage also contributes the greatest amount of LCD impacts (58%), but the manufacturing stage is also a significant contributor (33%) due to electricity consumed during manufacturing. LCD manufacturing electricity is linked to the Japanese electric grid, which derives 31% of its power from nuclear sources. By comparison, about 20% of the U.S. electric grid is powered by nuclear sources.

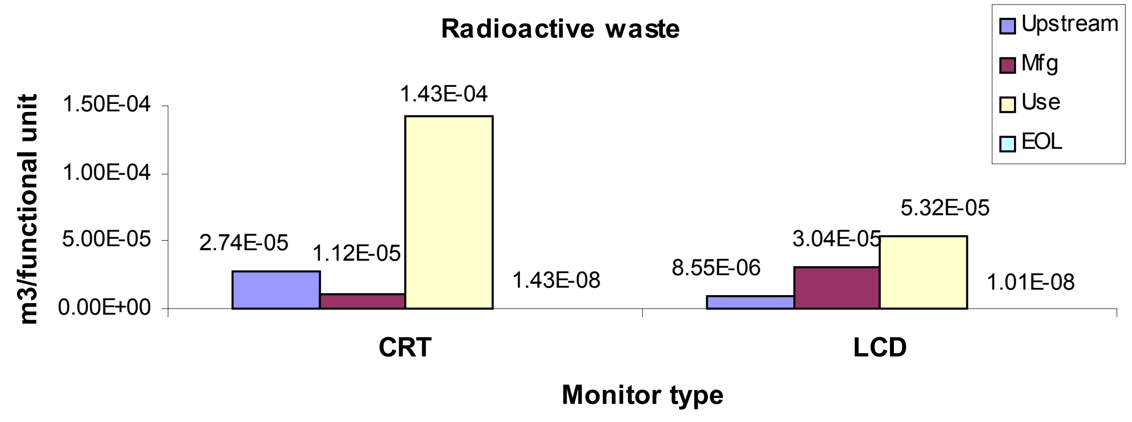

Figure 3-7. Radioactive waste impacts by life-cycle stage

Table 3-22 lists the materials that contribute to the top 99% of the CRT radioactive waste landfill use score and the LCI data type. Note that the LCI data for all of the materials in the table are from secondary sources or models. Low-level radioactive waste and depleted uranium from the U.S. electric grid are the radioactive materials being landfilled in the greatest quantities, followed by low-level radioactive waste from the production of steel used in the monitor. The latter radioactive waste is a byproduct of electricity production used in the manufacture of steel. It should be noted that the electricity generation data utilized in the steel inventory are from France (Glazebrook, 2001), where a large percentage of electricity is derived from nuclear sources. Therefore, these emissions may not be representative of emissions from steel production in some parts of Asia or in the United States. This issue is discussed further in the section on limitations and uncertainties, below.

Table 3-22. Top 99% of the CRT radioactive waste landfill use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Low-level radioactive waste	Model/secondary	61%
Use	U.S. electric grid	Uranium, depleted	Model/secondary	18%
Materials processing	Steel production, cold-rolled, semi-finished	Low-level radioactive waste	Secondary	9.0%
Manufacturing	Japanese electric grid	Low-level radioactive waste	Model/secondary	3.8%
Materials processing	Invar	Low-level radioactive waste	Secondary	2.6%
Materials processing	Ferrite manufacturing	Low-level radioactive waste	Secondary	2.5%
Manufacturing	Japanese electric grid	Uranium, depleted	Model/secondary	1.1%
Manufacturing	U.S. electric grid	Low-level radioactive waste	Model/secondary	0.97%

*Column may not add to 99% due to rounding.

Other significant contributors to the CRT radioactive waste score include low-level radioactive waste from electricity used in Japan during manufacturing, and low-level radioactive waste from invar and ferrite manufacturing. Invar is an alloy of nickel and iron. Like the steel data discussed above, the invar and ferrite manufacturing data also include emissions from electricity production. Finally, low-level radioactive waste from U.S. electricity consumed during the manufacturing stage contributes slightly less than 1% of the CRT radioactive waste landfill use impacts. The frit and PWB manufacturing processes consume this electricity. These are the only CRT components linked to the U.S. grid.

Table 3-23 lists the materials that contribute to the top 99% of the LCD radioactive waste landfill use results and the LCI data type. Note that LCI data for all of the primary contributors to this impact category are from secondary sources or modeled from secondary sources. Together, low-level radioactive waste and depleted uranium disposal from electricity consumed during use of the monitor account for about 57% of the LCD radioactive waste landfill use indicator, followed by low-level radioactive waste and depleted uranium disposal from electricity used during manufacturing (roughly 32%). Waste disposal from steel production is also a significant contributor at 8.7%. Like the CRT data discussed above, these emissions occur from electricity production in France and may not be representative of U.S. or some Asian practices.

Table 3-23. Top 99% of the LCD radioactive waste disposal impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Low-level radioactive waste	Model/secondary	44%
Manufacturing	Japanese electric grid	Low-level radioactive waste	Model/secondary	25%
Use	U.S. electric grid	Uranium, depleted	Model/secondary	13%
Materials processing	Steel production, cold-rolled, semi-finished	Low-level radioactive waste	Secondary	8.7%
Manufacturing	Japanese electric grid	Uranium, depleted	Model/secondary	7.5%

*Column may not add to 99% due to rounding.

3.3.4.4 Limitations and uncertainties

Landfill use pertains to the use of suitable and designated landfill space as a natural resource where the specified type of waste (solid, hazardous, or radioactive) is accepted. Landfill use impacts are characterized from solid, hazardous, or radioactive waste outputs with a disposition of landfill. Impact characterization is based on the volume of waste determined from the inventory mass amount of waste and materials density of each specific waste. Note that different countries may have different landfill designations for the final disposition of similar waste streams (e.g., a waste considered hazardous in the U.S. may be accepted in a solid waste landfill elsewhere). However, where possible, equivalent landfills (e.g., special waste landfills and hazardous waste landfills) were considered for these impact categories.

CRT and LCD impact results for the solid and radioactive waste landfill use categories were driven almost entirely by waste outputs reported in inventories from secondary sources. These inventories were not developed specifically for the CDP and therefore are subject to the limitations and uncertainties associated with secondary data (see Section 2.2.2 and 3.3.2). In particular, radioactive waste disposal from some of the upstream materials processing data may not be representative of conditions in the U.S. or parts of Asia. These data include emissions from electricity production within the materials inventory, which are the primary source of radioactive waste streams. For example, steel production data include the French electric grid, where a large percentage of the power supply comes from nuclear power plants. In addition, some of the upstream data may not be representative of current conditions, with steel production data covering the period from 1975 to 1990 and invar production data being from 1991.

CRT and LCD impact results for the hazardous waste landfill use category were dominated by monitor disposal at the end of their effective lives. Hazardous waste landfill disposal volumes were estimated based on the percent of monitors with hazardous waste landfilling as their final disposition, the monitor mass, and the material densities. However, data on the percentage of CRTs that are landfilled are not separated into hazardous and non-hazardous landfilling processes. Therefore, these percentages were estimated by the CDP, as described in Appendix I. Even less is known about the final disposition of LCDs, particulary since very few LCD desktop monitors have reached the end of their effective lives (and then, only if they have been damaged in some way). Therefore, the effect of different LCD EOL dispositions was evaluated in a sensitivity analysis (see Section 3.4.)

3.3.5 Global Warming

Figure 3-8 presents the CRT and LCD LCIA results for the global warming impact category, based on the impact assessment methodology presented in Section 3.1. Tables M-13 and M-14 in Appendix M list complete global warming results for the CRT and LCD, respectively. The life-cycle global warming indicators for the CRT and LCD were 695 and 593 kg of CO_2 equivalents per monitor, respectively. The CRT global warming indicators are driven by the use life-cycle stage, which contributes about 66% of the total. The manufacturing stage, which contributed 88% of the CRT energy consumption impacts, only contributes about 29% of the total global warming score. LCD global warming impacts, on the other hand, have the greatest contribution from the manufacturing life-cycle stage, which accounts for about 40% of the potential impacts in this category. Both the upstream (materials processing) and use life-cycle stages are also significant contributors to the LCD global warming results, accounting for 31% and 29% of the total, respectively.

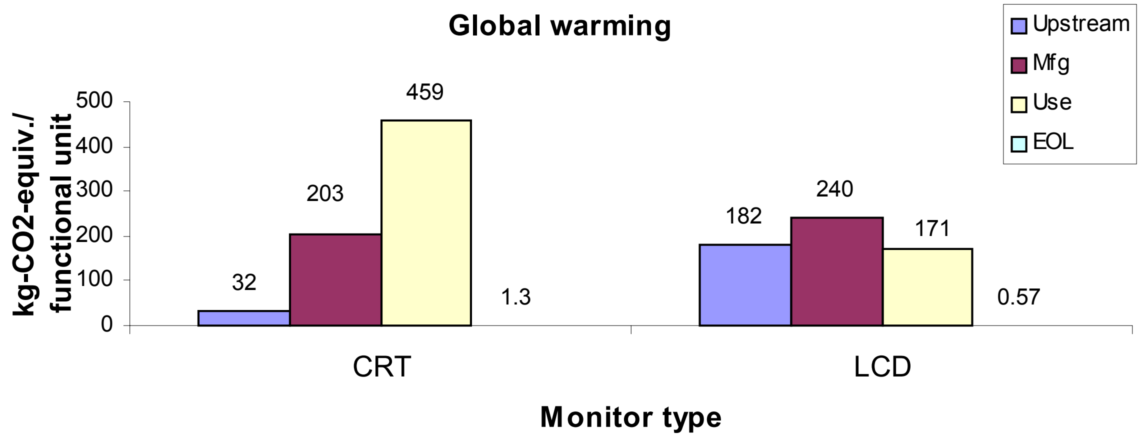

Figure 3-8. Global warming impacts by life-cycle stage

One might expect the distribution of global warming impacts across life-cycle stages to mirror those of energy consumption, as CO_2 is generally a large emission from electricity generation. However, as discussed in Section 3.3.3, CRT energy impacts are greatest in the manufacturing stage due to the large amounts of energy used to manufacture glass. Since the energy used in glass manufacturing is not only from electricity, but more so from other fuels (LPG, natural gas, and fuel oil), there is not a direct correlation between CRT global warming impacts and CRT energy impacts.

The distribution of LCD global warming impacts across life-cycle stages does mirror the distribution of LCD energy use impacts discussed in Section 3.3.3. However, as discussed below, the manufacturing stage global warming impacts for the LCD are being driven more by the use of sulfur hexafluoride (SF_6) in LCD monitor/module manufacturing than by the use of electricity.

3.3.5.1 Major contributors to the CRT global warming results

Table 3-24 presents the life-cycle inventory items contributing to the top 99% of the CRT global warming results and the LCI data type (primary, secondary, or model/secondary). As shown in the table, CRT global warming impacts are dominated by CO_2 emissions from electricity generation during use of the monitor, followed by CO_2 and methane emissions from producing LPG used as fuel in the CRT glass/frit process group. Together these three emissions contribute almost 89% of the CRT life-cycle global warming score. Carbon dioxide and methane emissions from a number of other processes also add to the CRT global warming score, as does nitrous oxide emissions from the LPG production process. It is likely that most of the CO_2 emissions from the materials processing life-cycle stage can be attributed to emissions from electricity generation or fuel combustion. As discussed in Section 2.2.2.1, the upstream materials processing inventories used in this study include data from electricity generation.

Note that almost all of the LCI data for global warming emissions are from secondary sources. This is because the CRT global warming results are dominated by CO_2 emissions from electricity generation, and electric grid data were either developed by the CDP from secondary sources or already included in the upstream, materials processing inventories from secondary sources.

Table 3-24. Top 99% of the CRT global warming impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Carbon dioxide	Model/secondary	64%
Manufacturing	LPG production	Carbon dioxide	Secondary	22%
Manufacturing	LPG production	Methane	Secondary	2.5%
Manufacturing	Japanese electric grid	Carbon dioxide	Model/secondary	2.2%
Use	U.S. electric grid	Methane	Model/secondary	1.9%
Materials processing	Steel production, cold-rolled, semi-finished	Carbon dioxide	Secondary	1.9%
Manufacturing	U.S. electric grid	Carbon dioxide	Model/secondary	1.0%
Manufacturing	LPG production	Nitrous oxide	Secondary	0.72%
Materials processing	Polycarbonate production	Carbon dioxide	Secondary	0.66%
Materials processing	Aluminum production	Carbon dioxide	Secondary	0.52%
End-of-Life	CRT incineration	Carbon dioxide	Secondary	0.51%
Manufacturing	CRT glass/frit mfg.	Carbon dioxide	Primary	0.40%
Materials processing	Invar	Carbon dioxide	Secondary	0.33%
Materials processing	Styrene-butadiene copolymer production	Carbon dioxide	Secondary	0.24%

*Column may not add to 99% due to rounding.

3.3.5.2 Major contributors to the LCD global warming results

Table 3-25 presents the life-cycle inventory items contributing to the top 99% of the LCD global warming results and the LCI data type (primary, secondary, or model/secondary). Sulfur hexafluoride used in LCD module manufacturing is the single largest contributor to LCD global warming impacts, followed by CO_2 emissions from electricity generation during the use stage, CO_2 and methane emissions from natural gas production, and CO_2 emissions from the generation of electricity used during manufacturing in Japan.

Table 3-25. Top 99% of the LCD global warming impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LCD monitor/module mfg.	Sulfur hexafluoride	Primary	29%
Use	U.S. electric grid	Carbon dioxide	Model/secondary	28%
Materials processing	Natural gas production	Carbon dioxide	Secondary	16%
Materials processing	Natural gas production	Methane	Secondary	12%
Manufacturing	Japanese electric grid	Carbon dioxide	Model/secondary	8.7%
Manufacturing	LPG production	Carbon dioxide	Secondary	1.2%
Materials processing	Steel production, cold-rolled, semi-finished	Carbon dioxide	Secondary	1.1%
Use	U.S. electric grid	Methane	Model/secondary	0.85%
Materials processing	PMMA sheet production	Carbon dioxide	Secondary	0.45%
Materials processing	Polycarbonate production	Carbon dioxide	Secondary	0.43%
Manufacturing	Natural gas production	Carbon dioxide	Secondary	0.35%
End-of-Life	LCD incineration	Carbon dioxide	Secondary	0.35%

*Column may not add to 99% due to rounding.

Sulfur hexafluoride is a potent global warming gas, with a global warming potential (GWP) equivalancy factor of 23,900 CO_2 equivalents (see Table K-2 in Appendix K). It is used as an etchant in a dry-etching process of amorphus silicon and SiNx films. The CO_2 and methane emissions from natural gas production can be attributed to the use of LNG as an ancillary material in LCD monitor/module manufacturing. However, as discussed in the section on non-renewable resource use (Section 3.3.2), only one LCD module manufacturer reported this use of LNG.

Carbon dioxide emissions (and, in one case, methane emissions) round out the remainder of the primary contributors to the LCD global warming indicator. Most of the carbon dioxide emissions occur from upstream processes and are due to electricity generation. With the exception of the SF_6 data, the LCI data for all of the top LCD global warming emissions are from secondary sources. Sulfur hexaflouride emissions data were developed by the CDP based on an emissions factor (0.45) applied to SF_6 inputs reported by LCD monitor/module manufacturers. The emissions factor is from the Intergovernmental Panel on Climate Change publication, *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (Penman *et al.*, 2000.)

3.3.5.3 Limitations and uncertainties

Global warming potential (GWP) refers to the warming that emissions of certain gases may contribute by building up in the atmosphere and trapping the earth's heat. As discussed in Section 3.1.2.4, the LCIA methodology for global warming impacts uses published GWP equivalency factors having effects in the 100-year time horizon. These effects are expected to be far enough into the future that releases occurring throughout the life cycle of a computer monitor would be within the 100-year timeframe.

The effects of the buildup of global warming gases in the atmosphere is still the subject of scientific debate, but in 1995 the Intergovernmental Panel on Climate Change (IPCC), representing the consensus of most climate scientists worldwide, concluded that "... the balance of evidence...suggests that there is a discernible human influence on global climate (IPCC, 1995)." Other than the limitations and uncertainties inherent in predicting future effects, most of the limitations and uncertainties in the CRT and LCD global warming results have to do with the LCI data on greenhouse gas emissions, which occur primarily from electricity generation processes.

As noted above, the U.S. and Japan electric grid inventories used in the CDP were developed by the CDP, and electric grids used with upstream processes are embedded in the upstream inventories. U.S. electric grid emissions of CO_2 are based on data in the EPA publication, *National Air Quality and Emissions Trends Report, 1997* (EPA, 1998), which were the best data available when the electric grid inventory data was developed and are expected to be reasonably accurate. However, the Japanese electric grid inventory was derived from the U.S. inventory based on the mix of fuels used in Japan. Because Japanese power plants may employ different pollution control devices, use fuels of different quality, or other factors, their greenhouse gas emissions could actually be higher or lower than those reported in the inventory.

Similarly, the electric grid inventories embedded in upstream, materials processing inventories may have differing geographic and temporal boundaries or may be representative of older technologies. Therefore, actual emissions of greenhouse gases could be higher or lower than reported. This is a common limitation of LCAs, which must often rely on secondary data sources to avoid the considerable time and resources required to collect primary data for every process.

3.3.6 Stratospheric Ozone Depletion

Figure 3-9 presents the CRT and LCD LCIA results for the stratospheric ozone depletion impact category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.5. Note that most of the CRT ozone depletion impacts occur from the use stage (50%) and the upstream, materials processing stages (45%), while most of the LCD ozone depletion impacts occur from the manufacturing stage (63%). As will be shown later, this is important because upstream and use stage data are primarily from secondary data sources, whereas manufacturing data were collected by the CDP. Tables M-15 and M-16 in Appendix M list complete stratospheric ozone depletion results for the CRT and LCD, respectively.

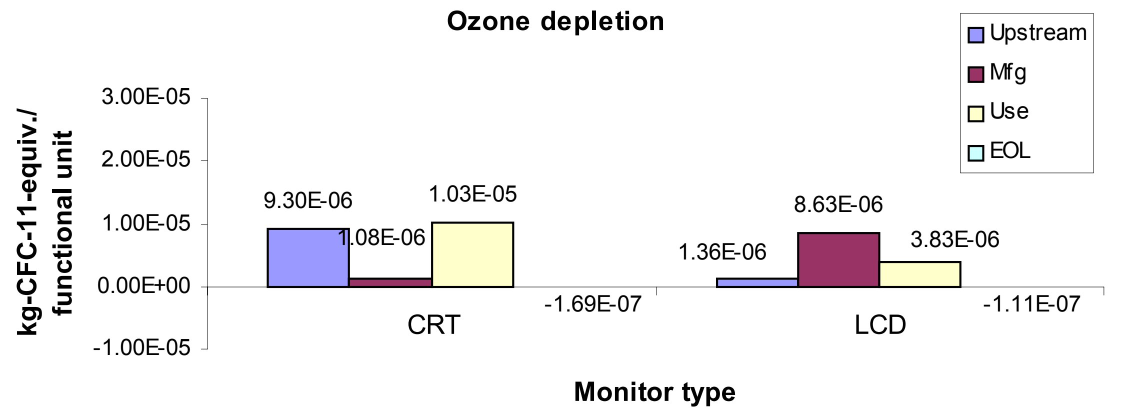

Figure 3-9. Ozone depletion impacts by life-cycle stage

The ozone depletion impact category indicator was 2.05E-05 kg of CFC-11 equivalents per monitor for the CRT and 1.37E-05 kg of CFC-11 equivalents per monitor for the LCD. However, for both the CRT and the LCD, many of the materials contributing to this impact category are listed as Class I ozone depleting substances in Title VI of the 1990 Clean Air Act Amendments, and therefore were required to be phased out of U.S. production by January 1, 1996. Production of these substances was also phased out in other developed countries under the Montreal Protocol and its Amendments and Adjustments, but continues today in some developing countries. An exception is bromomethane, which is a Class I substance that will not be completely phased out of production until 2005 (EPA, 2001a).

For a few of the phased out substances, a significant amount of inventory remained after production was phased out. However, most of these inventories are now exhausted, and Class I ozone depleting substances are rarely used by manufacturers in developed countries. If we delete the phased out substances from the CRT and LCD inventories, the CRT ozone depletion indicator is reduced 47% from 2.05E-05 to 1.09E-05 kg of CFC-11 equivalents per monitor, and the LCD result is reduced 14% from 1.37E-05 to 1.18E-05 kg of CFC-11 equivalents per monitor. These latter values are probably more representative of the temporal boundaries for primary data collected in the CDP LCA. Thus, when all data are included in the ozone depletion calculations, the CRT has a greater ozone depletion impact score than the LCD, but the results are switched (LCD greater than CRT) when phased out substances are removed from the inventory.

3.3.6.1 Major contributors to the CRT ozone depletion results

Table 3-26 lists the materials that contribute to the top 99% of the CRT life-cycle ozone depletion impact score and the LCI data type. Bromomethane emissions from electricity generated in the use stage are the single largest contributor to the CRT ozone depletion indicator, accounting for almost half of the total score. Most of the other materials in the table are emitted from materials production processes in the upstream, materials processing life-cycle stage. Exceptions are bromomethane emissions from the LPG production process (used to produce

LPG for the glass/frit process group), 1,1,1-trichloroethane emissions from electricity generation in the use stage, and bromomethane emissions from electricity used in manufacturing.

Table 3-26. Top 99% of the CRT stratospheric ozone depletion impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score[a]
Use	U.S. electric grid	Bromomethane[b]	Model/secondary	49%
Materials processing	ABS production	HALON-1301[b]	Secondary	20%
Materials processing	Aluminum production	HALON-1301[b]	Secondary	14%
Materials processing	Invar	HALON-1301[b]	Secondary	5.9%
Manufacturing	LPG production	Bromomethane[b]	Secondary	3.7%
Materials processing	Lead	HALON-1301[b]	Secondary	2.6%
Materials processing	Steel production, cold-rolled, semi-finished	HALON-1301[b]	Secondary	2.0%
Use	U.S. electric grid	1,1,1-Trichloroethane[b]	Model/secondary	1.1%
Manufacturing	U.S. electric grid	Bromomethane[b]	Model/secondary	0.78%

[a] Column may not add to 99% due to rounding.

[b] Class I substance as listed in Title VI of the Clean Air Act Amendments.

Note that all of the materials listed in Table 3-26 are Class I ozone depleting substances. As discussed above, all of these substances except bromomethane were phased out of production by January 1, 1996. Note also that all of the LCI data for the materials in the table are from secondary sources. For both of these reasons, the LCI data for the materials in the table are highly uncertain. This is discussed further under limitations and uncertainties, below.

3.3.6.2 Major contributors to the LCD ozone depletion results

Table 3-27 lists the top contributors to the LCD life-cycle stratospheric ozone depletion indicator and the LCI data type. Together HCFC-225cb and HCFC 225ca used in the LCD panel components process group account for 59% of the LCD ozone depletion indicator. Note that HCFC 225cb and HCFC 225ca are Class II ozone depleting substances that are not scheduled for phaseout until 2015. [Under U.S. regulations and the Montreal Protocol and its Amendments and Adjustments these substances can not be produced or imported after 2015, except for use as refrigerants in equipment manufactured before January 1, 2020 (EPA, 2001b).] Also note that the impact scores for these materials are based on primary LCI data collected from manufacturers. Therefore, these data are considered to be more reliable than data for Phase I substances from secondary sources.

Table 3-27. Top 99% of the LCD stratospheric ozone depletion use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score[a]
Manufacturing	LCD panel components	HCFC-225cb[b]	Primary	34%
Use	U.S. electric grid	Bromomethane[c]	Model/secondary	27%
Manufacturing	LCD panel components	HCFC-225ca[b]	Primary	25%
Materials processing	Aluminum production (virgin)	HALON-1301[c]	Secondary	7.8%
Manufacturing	Japanese electric grid	Bromomethane[c]	Model/secondary	3.1%
Materials processing	Steel production, cold-rolled, semi-finished	HALON-1301[c]	Secondary	1.4%

[a] Column may not add to 99% due to rounding.
[b] Class II substance as listed in Title VI of the Clean Air Act Amendments.
[c] Class I substance as listed in Title VI of the Clean Air Act Amendments.

Other significant contributors to the LCD ozone depletion score include bromomethane emissions from electricity generation in the United States and Japan, and halon emissions from upstream, materials processing stages. As noted above in the discussion of CRT ozone depletion results, the halons were phased out of production in 1996, which suggests that these data are not representative of current conditions. Bromomethane is still being produced, but bromomethane emissions data are also uncertain as will be discussed in the section on limitations and uncertainties, below.

3.3.6.3 Limitations and uncertainties

Both the CRT and LCD life-cycle stratospheric ozone depletion results are highly uncertain due to the inclusion of a number of Class I ozone depleting substances in inventories from secondary sources. As discussed above, except for bromomethane, developed countries that are parties to the Montreal Protocol and its Amendments and Adjustments phased out the production of Class I substances by 1996. To better assess the uncertainties in these results, Table 3-28 lists the geographic and temporal boundaries for the life-cycle inventories of the process groups listed in tables 3-26 and 3-27, above.

Table 3-28. Geographic and temporal boundaries of inventories contributing to the CRT and/or LCD ozone depletion indicator results

Process group	Geographic boundaries	Temporal boundaries
ABS production	Germany, Italy, Netherlands	1997
Aluminum production	Not provided	Not provided
Invar production	Multiple countries	1991 (nickel), Not provided (lead)
Japanese electric grid	U.S. and Japan[a]	1993[b]
LCD panel components	Japan	1998
Lead production	Not provided	Not provided
LPG production	Mainly U.S.	1983-1993
Steel production	Multiple countries	1975-1990
U.S. electric grid	U.S.	1993[b]

[a] Based on the U.S. electric grid inventory modified to account for the fuel mix used in Japan.
[b] Date of stack tests from which bromomethane emission factor was developed (from EPA Web site: Emission Factor Documentation for AP-42 Section 1.1: Bituminous and Subbituminous Coal Combustion. http://www.epa.gov/ttn/chief/ap42/ch01/bgdocs/b01s01.pdf.)

The most recent data are for LCD panel components manufacturing, which are primary data collected from manufacturers in Japan by the CDP and expected to be of better quality than older data from secondary sources. Data for ABS production are also fairly recent, dating from 1997. However, the temporal boundaries for most of the data are either not listed in the inventories, or pre-date the Class I substance production phase out. In addition, most of the data are from Europe and/or the United States, where very few Class I ozone depleting substances are currently used. Thus, we suspect that emissions of Class I substances reported in the inventories no longer occur, indicating that the CRT and LCD life-cycle impact results should be reduced to 2.05E-05 kg of CFC-11 equivalents per monitor for the CRT, and 1.37E-05 kg of CFC-11 equivalents per monitor for the LCD.

Bromomethane is a Class I ozone depleting substance that has not yet been phased out of production and is emitted during coal combustion to produce electricity. Bromoethane emissions from electricity production are estimated from an emission factor reported in AP-42, the EPA compilation of air pollutant emission factors (EPA, 1996). EPA (1996) provides an emission factor rating that is, "an overall assessment of how good a factor is, based on both the quality of the test(s) or information that is the source of the factor and on how well the factor represents the emission source." The bromomethane emissions factor rating is "D," or below average, indicating CDP data quality for bromomethane emissions from electricity generation is also below average.

In conclusion, it appears that most of the Class I substance emissions data are highly uncertain or of below average quality. Manufacturing data collected by the CDP, which includes emissions of Class II substances, are of better quality and expected to be more representative of current conditions. When all data are included in the ozone depletion calculations, the CRT has a greater ozone depletion impact score than the LCD. However, if we remove phased out substances from the inventory, the results are switched with the LCD having a greater score in this category than the CRT.

3.3.7 Photochemical Smog

Figure 3-10 presents the CRT and LCD LCIA results for the photochemical smog impact category by life-cycle stage. These results were calculated using the impact assessment methodology presented in Section 3.1.2.6. Tables M-17 and M-18 in Appendix M list complete results for the CRT and LCD, respectively. One 17" CRT monitor produces 0.171 kg of ethene equivalents throughout its life cycle, while a functionally equivalent 15" LCD monitor produces 0.141 of ethene equivalents. The CRT photochemical smog impact score is dominated by emissions during the manufacturing stage (71% of total); the LCD impact score is dominated by emissions during the upstream, materials processing stages (91% of total). However, as discussed below, it is fossil fuel production processes that emit the majority of smog forming emissions during the life-cycle of either monitor type. Both the CRT and LCD receive a slight credit on emissions of smog forming chemicals at the end of their effective lives due to energy recovery from incineration processes.

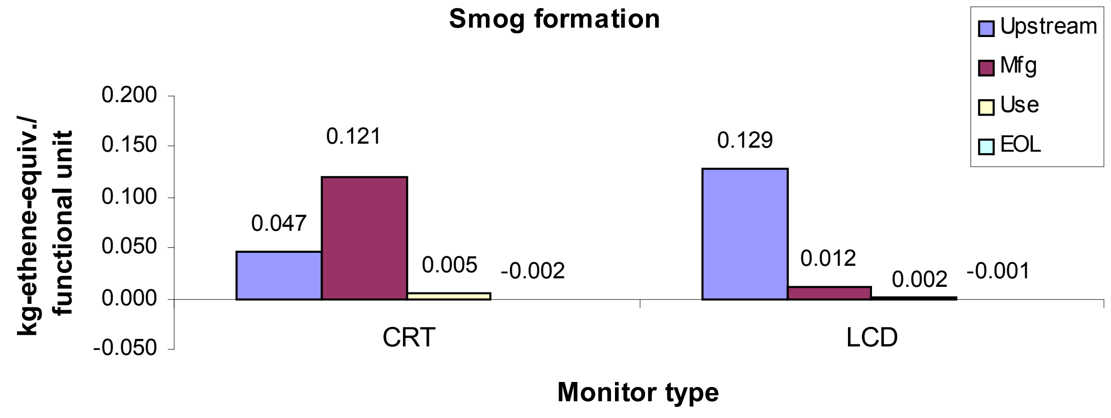

Figure 3-10. Smog formation impacts by life-cycle stage

<u>3.3.7.1 Major contributors to the CRT photochemical smog results</u>

Table 3-29 lists the materials that contribute to the top 99% of the CRT photochemical smog indicator result. The LPG production process alone, which emits various unspeciated hydrocarbons, benzene, aldehydes, ethane, and formaldehyde, accounts for almost 67% of CRT photochemical smog impacts. As noted earlier in the discussion of other impact category indicators, most of this LPG is used as a fuel source in CRT glass manufacturing. However, CRT glass energy data reported in the three data sets received by the CDP were highly variable and therefore the subject of a sensitivity analysis (see Section 3.4).

Other materials responsible for more than 1% of the CRT photochemical smog score include the following: (1) hydrocarbon (methane and nonmethane) emissions associated with steel production, (2) methane emissions from electricity generation during the use stage, (3) toluene emissions from CRT tube manufacturing, (4) nonmethane hydrocarbon emissions associated with ABS production, and (5) nonmethane hydrocarbon emissions associated with polycarbonate production. Note that the inventory for each upstream material (e.g., steel production, ABS production, etc.) contains data from the raw materials extraction, materials manufacture, and (usually) electricity generation processes. Therefore, hydrocarbon emissions associated with steel production, for example, could be from one of many individual processes, such as the steel production process itself, from fuels consumed during the mining of ore, or from the combustion of fuels as an energy source during steel manufacturing.

Table 3-29. Top 99% of the CRT photochemical smog impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	Hydrocarbons, unspeciated	Secondary	36%
Manufacturing	LPG production	Nonmethane hydrocarbons, unspeciated	Secondary	25%
Materials processing	Steel production, cold-rolled, semi-finished	Nonmethane hydrocarbons, unspeciated	Secondary	19%
Manufacturing	LPG production	Methane	Secondary	3.4%
Use	U.S. electric grid	Methane	Model/secondary	2.6%
Materials processing	Steel production, cold-rolled, semi-finished	Hydrocarbons, unspeciated	Secondary	2.0%
Manufacturing	LPG production	Benzene	Secondary	1.6%
Manufacturing	CRT tube mfg.	Toluene	Primary	1.3%
Materials processing	ABS production	Nonmethane hydrocarbons, unspeciated	Secondary	1.3%
Materials processing	Polycarbonate production	Nonmethane hydrocarbons, unspeciated	Secondary	1.1%
Materials processing	Aluminum production	Nonmethane hydrocarbons, unspeciated	Secondary	0.86%
Manufacturing	Natural gas production	Nonmethane hydrocarbons, unspeciated	Secondary	0.53%
Materials processing	ABS production	Nonmethane hydrocarbons, unspeciated	Secondary	0.41%
Manufacturing	LPG production	Aldehydes	Secondary	0.39%
Materials processing	Stryene-butadiene copolymer production	Hydrocarbons, remaining unspeciated	Secondary	0.39%
Materials processing	Invar	Nonmethane hydrocarbons, unspeciated	Secondary	0.32%
Manufacturing	Fuel oil #6 production	Hydrocarbons, unspeciated	Secondary	0.31%
Manufacturing	LPG production	Formaldehyde	Secondary	0.29%
Materials processing	Lead	Nonmethane hydrocarbons, unspeciated	Secondary	0.21%
Manufacturing	Fuel oil #6 production	Nonmethane hydrocarbons, unspeciated	Secondary	0.21%
Manufacturing	Natural gas production	Methane	Secondary	0.21%
Manufacturing	LPG production	Ethane	Secondary	0.18%
Manufacturing	CRT tube mfg.	Xylene (mixed isomers)	Primary	0.17%
Manufacturing	LPG production	Pentane	Secondary	0.16%

Table 3-29. Top 99% of the CRT photochemical smog impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	Natural gas production	Benzene	Secondary	0.14%

*Column may not add to 99% due to rounding.

3.3.7.2 Major contributors to the LCD photochemical smog results

Table 3-30 lists the materials that contribute to the top 99% of the LCD life-cycle photochemical smog results. LCD results are dominated by unspeciated hydrocarbon emissions, methane emissions, and benzene emissions from natural gas production in the materials processing life-cycle stage, which together account for about 75% of the total. This natural gas is used as an ancillary material by one LCD monitor/module manufacturer. Other LCD monitor/module manufacturers reported using LNG as a fuel, but not as an ancillary number. A number of other materials and processes contribute more than 1% of the total LCD photochemical smog score, most notably unspeciated, nonmethane hydrocarbon emissions associated with steel production. As noted above under the CRT results, the latter hydrocarbon emissions could occur from any one of various processes (e.g., ore mining, steel production, electricity generation, etc.) wrapped into the steel production inventory.

Table 3-30. Top 99% of the LCD photochemical smog impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Natural gas production	Nonmethane hydrocarbons, unspeciated	Secondary	45%
Materials processing	Natural gas production	Methane	Secondary	17%
Materials processing	Natural gas production	Benzene	Secondary	12%
Materials processing	Steel production, cold-rolled, semi-finished	Nonmethane hydrocarbons, unspeciated	Secondary	11%
Manufacturing	LCD monitor/module mfg.	Isopropyl alcohol	Primary	2.5%
Manufacturing	LPG production	Hydrocarbons, unspeciated	Secondary	2.1%
Manufacturing	LPG production	Nonmethane hydrocarbons, unspeciated	Secondary	1.4%
Materials processing	Natural gas production	Hydrocarbons, unspeciated	Secondary	1.2%
Materials processing	Steel production, cold-rolled, semi-finished	Hydrocarbons, unspeciated	Secondary	1.2%
Use	U.S. electric grid	Methane	Model/secondary	1.2%
Manufacturing	Natural gas production	Nonmethane hydrocarbons, unspeciated	Secondary	1.0%
Materials processing	PMMA sheet production	Nonmethane hydrocarbons, unspeciated	Secondary	0.87%
Materials processing	Polycarbonate production	Nonmethane hydrocarbons, unspeciated	Secondary	0.73%
Manufacturing	Natural gas production	Methane	Secondary	0.39%

Table 3-30. Top 99% of the LCD photochemical smog impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Aluminum production	Nonmethane hydrocarbons, unspeciated	Secondary	0.39%
Materials processing	PET resin production	Nonmethane hydrocarbons, unspeciated	Secondary	0.36%

*Column may not add to 99% due to rounding.

3.3.7.3 Limitations and uncertainties

Photochemical smog indicators are calculated using the mass of a chemical released to air per functional unit and the chemical-specific partial equivalency factor. The equivalency factor is a measure of the chemical's photochemical oxidant creation potential (POCP) compared to the reference chemical ethylene. As noted in Section 3.1.2.6, photochemical smog impacts are based on partial equivalency because some chemicals cannot be converted into POCP equivalency factors (e.g., nitrogen oxide). The inability to develop equivalency factors for some chemicals is a limitation of the photochemical smog impact assessment methodology.

The CRT impact score for photochemical smog formation is being driven by the process for producing the large amount of LPG used in CRT glass manufacture. However, as discussed in Section 2.3.3.3 and previous subsections of this Section 3.3, the three sets of glass manufacturing energy data received by the CDP were highly variable, making the average glass energy inputs used in the baseline analysis uncertain. Therefore, the emissions of smog forming chemicals from LPG production, which are based on the glass LPG inputs, are also uncertain. CRT glass energy inputs were subjected to a sensitivity analysis. Sensitivity results are discussed in Section 3.4.

The LCD impact score for photochemical smog formation is being driven by the natural gas production process to produce the large amount of LNG used as an ancillary material during LCD monitor/module manufacturing. However, as discussed earlier, only one LCD monitor/module manufacturer reported this use of LNG, which indicates the average LNG inputs used in the LCD inventory may be unduly high. Therefore, the mass of smog forming chemical emissions from the natural gas production process, which are based on the amount of ancillary LNG inputs, may also by unduly high.

The majority of the CRT and LCD photochemical smog results are based on life-cycle inventories from secondary sources and are therefore subject to the limitations and uncertainties associated with secondary data, discussed previously. In particular, see Section 3.3.1.1 for a detailed discussion of limitations and uncertainties in the LPG and natural gas production data.

3.3.8 Acidification

Figure 3.11 presents the CRT and LCD LCIA results for the acidification impact category, based on the impact assessment methodology presented in Section 3.1.2.7. Tables M-19 and M-20 in Appendix M list complete results for the CRT and LCD, respectively. The life-cycle acidification impact indicator result is 5.25 kg of SO_2 equivalents per monitor for the CRT and 2.96 kg of SO_2 equivalents per monitor for the LCD. As might be expected, acidification impacts are greatest in the use stage for both monitor types, due to the emissions of SO_x and NO_x from U.S. power plants. Use stage impacts are more dominant for the CRT (65% of life-cycle acidification impacts) than the LCD (43%) due to the relatively large amount of power consumed during use by the less energy-efficient CRT.

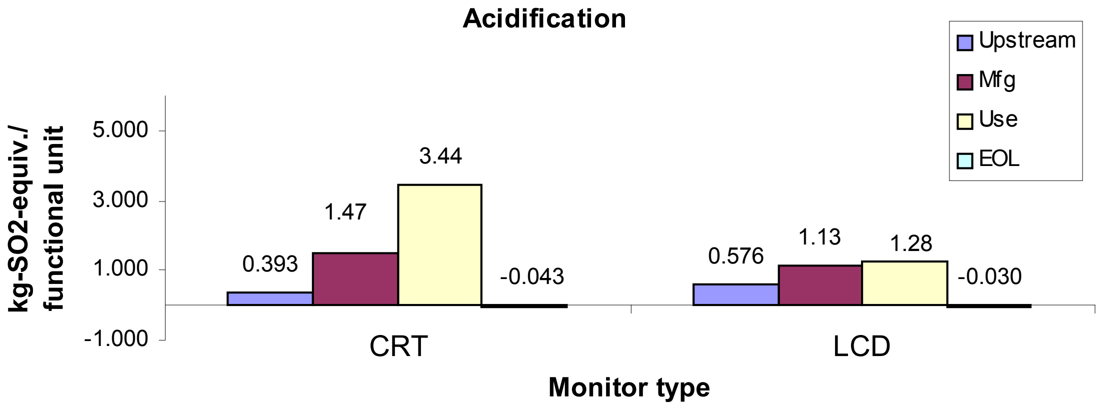

Figure 3-11. Acidification impacts by life-cycle stage

Emissions from manufacturing processes account for 28% of CRT acidification impacts and 38% of LCD acidification impacts. Material processing is responsible for about 7 and 19% of CRT and LCD impacts in this category, respectively. Both technologies receive a slight credit on acidification impacts during the EOL stage due to an energy credit from incineration processes with energy recovery, which offset some of the impacts from electricity production.

3.3.8.1 Major contributors to the CRT acidification results

Table 3-31 lists the materials that contribute to the top 99% of the CRT acidification impacts score and their LCI data type. SO_2 and NO_x emissions from the U.S. electric grid are the two largest contributors to the CRT acidification indicator, together accounting for 63% of the total. SO_x and NO_x emissions from the LPG production process are also significant, contributing about 23%. As noted previously, most of the LPG from this production process is used to manufacture CRT glass, but the mass of LPG inputs is uncertain and the basis of a sensitivity analysis later in this chapter (see Section 3.4).

Other materials that contribute more than one percent of the CRT acidification indicator are SO_2 emissions from invar production, hydrochloric acid emissions from electricity generation during the use stage, and sulfur dioxide emissions from electricity used in manufacturing. Note that most of the LCI data for materials in Table 3-31 are from secondary sources.

Table 3-31. Top 99% of the CRT acidification impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	47%
Use	U.S. electric grid	Nitrogen oxides	Model/secondary	16%
Manufacturing	LPG production	Sulfur oxides	Secondary	15%
Manufacturing	LPG production	Nitrogen oxides	Secondary	7.6%
Materials processing	Invar	Sulfur dioxide	Secondary	4.8%
Use	U.S. electric grid	Hydrochloric acid	Model/secondary	1.8%
Manufacturing	Japanese electric grid	Sulfur dioxide	Secondary	1.6%
Manufacturing	U.S. electric grid	Sulfur dioxide	Model/secondary	0.76%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur dioxide	Secondary	0.73%
Manufacturing	CRT glass/frit manufacturing	Nitrogen oxides	Primary	0.59%
Manufacturing	Japanese electric grid	Nitrogen oxides	Model/secondary	0.54%
Use	U.S. electric grid	Hydrofluoric acid	Model/secondary	0.41%
Materials processing	Aluminum production	Sulfur dioxide	Secondary	0.40%
Materials processing	Polycarbonate production	Nitrogen dioxide	Secondary	0.26%
Manufacturing	U.S. electric grid	Nitrogen oxides	Model/secondary	0.25%
Materials processing	Polycarbonate production	Sulfur dioxide	Secondary	0.23%
Manufacturing	LPG production	Nitrous oxide	Secondary	0.22%

*Column may not add to 99% due to rounding.

3.3.8.2 Major contributors to the LCD acidification impact results

Table 3-32 lists the materials responsible for the top 99% of the LCD acidification impact results and the LCI data type. Sulfur dioxide emissions from the U.S. electric grid during the use stage are the greatest contributor at 31%, followed by NO_x from natural gas production in the materials processing stage. The latter process produces natural gas used by one LCD monitor/module manufacturer as an ancillary material, indicating the LCD monitor/module manufacturing process group is ultimately responsible for this contribution to the impact score. However, as noted previously, only one LCD monitor/module manufacturer reported the ancillary use of LNG. Other LCD monitor/module manufacturers reported using LNG as a fuel, but not as an ancillary material. NO_x, ammonia, hydrofluoric acid, and hydrochloric acid emissions from LCD monitor/module manufacturing contribute another 22% of the LCD acidification impact score. LCD monitor/module manufacturing data were collected directly by the CDP from manufacturers in Asia.

NO_x emissions from the U.S. electric grid during the use stage, and SO_x and NO_x emissions from the Japanese electric grid during manufacturing are also among the top contributors to the LCD acidification results. LCI data for these process groups were developed by the CDP from secondary sources.

Table 3-32. Top 99% to the LCD acidification impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	31%
Materials processing	Natural gas prod.	Nitrogen oxides	Secondary	15%
Manufacturing	LCD monitor/module mfg.	Nitrogen oxides	Primary	13%
Use	U.S. electric grid	Nitrogen oxides	Model/secondary	10%
Manufacturing	Japanese electric grid	Sulfur dioxide	Model/secondary	9.8%
Manufacturing	LCD monitor/module mfg.	Ammonia	Primary	4.0%
Manufacturing	Japanese electric grid	Nitrogen oxides	Model/secondary	3.2%
Manufacturing	LCD monitor/module mfg.	Hydrofluoric acid	Primary	2.8%
Manufacturing	LCD monitor/module mfg.	Hydrochloric acid	Primary	1.8%
Manufacturing	LPG production	Sulfur oxides	Secondary	1.3%
Use	U.S. electric grid	Hydrochloric acid	Model/secondary	1.2%
Manufacturing	LCD backlight	Nitrogen oxides	Primary	0.70%
Materials processing	Natural gas production	Ammonia	Secondary	0.69%
Materials processing	Natural gas production	Sulfur oxides	Secondary	0.65%
Manufacturing	LPG production	Nitrogen oxides	Secondary	0.65%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur oxides	Secondary	0.64%
Materials processing	PMMA sheet production	Sulfur oxides	Secondary	0.44%
Manufacturing	Natural gas production	Nitrogen oxides	Secondary	0.35%
Use	U.S. electric gird	Hydrofluoric acid	Model/secondary	0.27%

*Column may not add to 99% due to rounding.

3.3.8.3 Limitations and uncertainties

Acidification impact characterization is a function of the mass of an acid-forming chemical emitted to air and the acidification potential (AP) equivalency factor for that chemical. The AP equivalency factor is the number of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released compared to SO_2. This is a full equivalency approach to impact characterization where all substances are addressed in a unified, technical model, which lends more certainty to the characterization results than partial equivalency factors discussed with regard to photochemical smog (Section 3.3.7).

For the CRT, and less so for the LCD, impact results are being driven primarily by SO_2 and NO_x emissions from U.S. power plants during use of the monitor by the consumer. As discussed in Section 3.3.5 and noted above, the U.S. and Japanese electric grid inventories were developed by the CDP from secondary sources. U.S. electric grid emissions of the criteria pollutants, including SO_2 and NO_x, are based on data in the EPA publication, *National Air Quality and Emissions Trends Report, 1997* (EPA, 1998), which were the best data available when the electric grid inventory data was developed and are expected to be reasonably accurate. However, the Japanese electric grid inventory was derived from the U.S. inventory based on the mix of fuels used in Japan. Because Japanese power plants may employ different pollution control devices, use fuels of different quality, or other factors, their emissions could actually be higher or lower than those reported in the inventory.

LCI data for many of the other primary contributors to the CRT acidification impact category are from existing LCI databases. The limitations and uncertainties associated with these data have been discussed extensively in other subsections of this chapter and pertain here. On the other hand, LCI data for many of the other primary contributors to the LCD acidification indicator results were collected directly by the CDP from manufacturers in Asia. These data are considered to be of better quality since they were collected to meet the goals, objectives and temporal and spatial boundaries of the CDP.

3.3.9 Air Particulates

Figure 3-12 presents the CRT and LCD LCIA results for the air particulates impact category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.8. Tables M-21 and M-22 in Appendix M list complete air particulates results for the CRT and LCD, respectively.

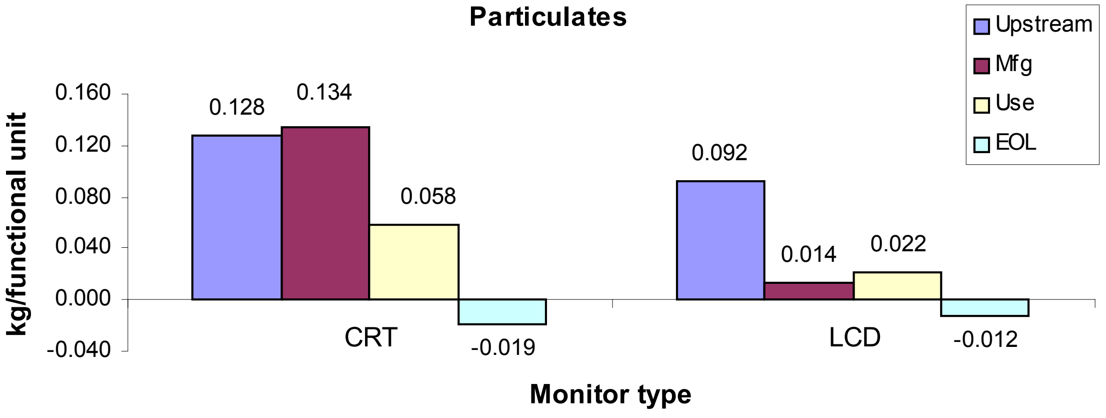

Figure 3-12. Particulates impacts by life-cycle stage

The life-cycle air particulates indicator is 0.30 kg of air particulates per monitor for the CRT and 0.115 kg of air particulates per monitor for the LCD. Recall from Section 3.1.2.8 that air particulates impact results are ideally based on release amounts of particulate matter with average aerodynamic diameter less than 10 micrometers (PM_{10}) to the air. This is the size of particulate matter that is most damaging to the respiratory system. However, as will be shown later in this section, a significant portion of the particulate emissions data for both monitor types do not specify a particulate size. This makes it more difficult to draw conclusions about the relative life-cycle air particulate impacts of the CRT and LCD.

The manufacturing and upstream materials processing stages have almost equal contribution to CRT air particulate impacts, at 45% of the total for the manufacturing stage and 43% of the total for the upstream stages. LCD impacts, on the other hand, are dominated by particulate emissions during the upstream, materials processing stages, which contribute 80% of the total score. Both technologies receive a substantial reduction in life-cycle air particulate impacts at EOL due to an energy credit from incineration with energy recovery. The energy credit, which is from incineration with energy recovery, is applied to electric power production where it offsets some particulate emissions that would otherwise occur from electrical power production.

3.3.9.1 Major contributors to the CRT air particulates impact results

Table 3-33 lists the materials that contribute to the top 99% of the CRT air particulates impact score and their LCI data type. PM emissions from LPG production are the single largest contributor to the overall score, at 43% of the total. This LPG is primarily an energy source in CRT glass manufacturing, indicating the glass/frit process group is the ultimate source of these air particulate emissions. As noted previously, CRT glass energy inputs are the subject of a sensitivity analysis, discussed in Section 3.4.

Other major contributors to the CRT air particulates impact results are PM emissions from the steel production process group, PM_{10} emissions from the U.S. electric grid during the use stage, and PM emissions from aluminum production processes. Note that the inventories for steel and aluminum production combine data from the raw materials extraction, materials manufacture, and electricity generation processes. The PM emissions reported for the material production process group could be from any one of these individual processes, but particulate matter emissions are most often associated with combustion processes.

Table 3-33. Top 99% of the CRT air particulates impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	PM	Secondary	43%
Materials processing	Steel production, cold-rolled, semi-finished	PM	Secondary	35%
Use	U.S. electric grid	PM-10	Model/secondary	19%
Materials processing	Aluminum production	PM	Secondary	3.0%

*Column adds to greater than 99% due to an offset of emissions from incineration with energy recovery at EOL.

As shown in Table 3-33**,** the impact scores associated with the LPG, steel, and aluminum production process groups—82% of CRT air particulates impacts—are based on emissions of PM instead of emissions of PM_{10}. This could be a matter of different terminology used in the secondary data sets for these process groups (that is, PM is used to represent PM_{10}), or it could represent a broader class of particulate emissions, of which PM_{10} emissions would be a subset. If the latter case is true, it is likely that CRT air particulate impacts are overstated.

3.3.9.2 Major contributors to the LCD air particulates impact results

Table 3-34 lists the materials that contribute to the top 99% of the LCD air particulates impact score and their LCI data type. PM emissions from steel production are the largest contributor to the overall score, followed by PM emissions from natural gas production. Natural gas from this process supplies the LNG used as an ancillary material by one LCD monitor/module manufacturer.

Other major contributors to the LCD air particulates impact results are PM_{10} emissions from the U.S. electric grid during the use stage and from the Japanese electric grid during manufacturing, and PM emissions from LPG production. LPG from the latter process supplies energy to the LCD glass manufacturing process.

Table 3-34. Top 99% of the LCD air particulates impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Steel production, cold-rolled, semi-finished	PM	Secondary	45%
Materials processing	Natural gas production	PM	Secondary	25%
Use	U.S. electric grid	PM-10	Model/secondary	19%
Manufacturing	Japanese electric grid	PM-10	Model/secondary	5.9%
Manufacturing	LPG production	PM	Secondary	5.4%

*Column adds to greater than 99% due to an offset of emissions from incineration with energy recovery at EOL.

As shown in Table 3-34, the impact scores associated with the steel, natural gas, and LPG production process groups—roughly 75% of LCD air particulates impacts—are based on emissions of PM instead of emissions of PM_{10}. As with the CRT, air particulate impacts should be based on PM_{10} emissions, indicating LCD air particulate impacts may be overstated.

3.3.9.3 Limitations and uncertainties

The CDP LCIA methodology for air particulates is based on emissions of PM_{10} to air, which is the size of particulate matter that is most damaging to the respiratory system. However, as noted in Tables 3-33 and 3-34, the majority of the CRT and LCD impacts were calculated from emissions of "PM" rather than PM_{10}. This could be a matter of different terminology used in the secondary data sets for these process groups, or it could represent a broader class of particulate emissions, of which PM_{10} emissions would be a subset. If the latter case is true, it is likely that both the CRT and LCD air particulate impacts are overstated.

The LCI data for all of the major contributors to both the CRT and LCD were either developed by the CDP from secondary sources (e.g., the U.S. and Japanese electric grids) or are from secondary LCI data sets (e.g., the fuel and upstream materials production processes). The limitations and uncertainties associated with these data have been discussed in other subsections of this chapter and pertain here. Note that U.S. electric grid emissions of the criteria pollutant PM_{10} are based on data in the EPA publication, *National Air Quality and Emissions Trends Report, 1997* (EPA, December, 1998, EPA/454/R-98-016), and are expected to be reasonably accurate.

Finally, the amount of LPG used to produce CRT glass, which is ultimately driving the CRT air particulates results, is also uncertain due to the large variability in CRT glass energy inputs received from glass manufacturers. See Section 3.4 for a sensitivity analysis of CRT glass energy inputs.

3.3.10 Water Eutrophication

Figure 3-13 presents the CRT and LCD LCIA results for the water eutrophication impact category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.9. Tables M-23 and M-24 in Appendix M are complete results for the CRT and LCD, respectively.

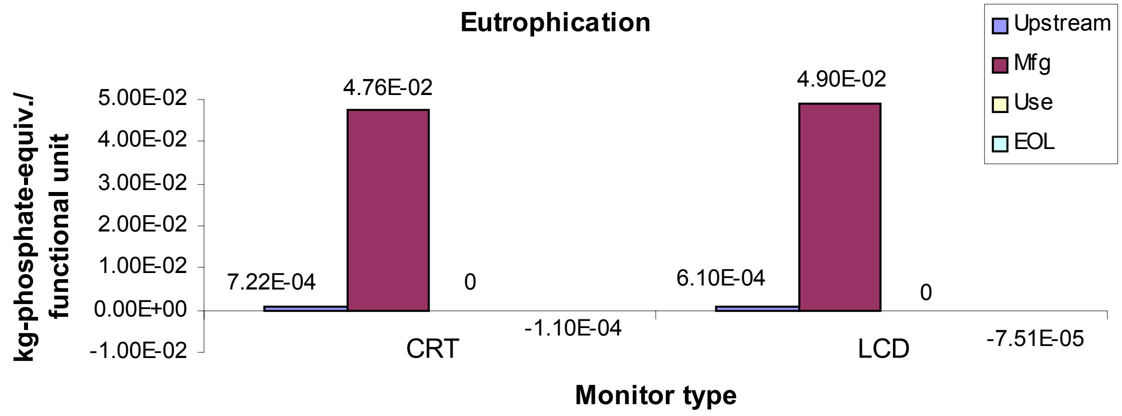

Figure 3-13. Eutrophication impacts by life-cycle stage

The life-cycle water eutrophication indicators are 0.048 kg of phosphate equivalents for the CRT and 0.050 kg of phosphate equivalents for the LCD. Results for both the CRT and LCD are completely dominated by emissions from the manufacturing stage, which accounts for 99% of the indicator for both technologies. Both technologies have negative scores at the end-of-life due to incineration with energy recovery. The energy recovery offsets some of the water emissions from the electricity generation inventory included in the incineration data set.

3.3.10.1 Major contributors to the CRT water eutrophication impact results

Table 3-35 lists the materials that contribute to the top 99% of the CRT water eutrophication results. Together, chemical oxygen demand (COD) and ammonia ions from the LPG production process group account for about 91% of the total score. Most of the LPG from this process is used as an energy source in CRT glass manufacturing (see Section 3.4 for the sensitivity analysis of CRT glass energy inputs). Emissions of nitrogen, COD and phosphorus from the CRT tube manufacturing process group contribute about seven percent of the CRT water eutrophication impacts. COD and other nitrogen emissions from steel production are the remaining top contributors to the CRT eutrophication score. LPG and steel production data are from secondary sources, while the CRT tube manufacturing outputs are primary data collected by the CDP.

Table 3-35. Top 99% of the CRT water eutrophication impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	COD	Secondary	72%
Manufacturing	LPG production	Ammonia ions	Secondary	19%
Manufacturing	CRT tube manufacturing	Nitrogen	Primary	6.3%
Materials processing	Steel production, cold-rolled, semi-finished	Other nitrogen	Secondary	0.37%
Materials processing	Steel production, cold-rolled, semi-finished	COD	Secondary	0.33%
Manufacturing	CRT tube manufacturing	COD	Primary	0.33%
Manufacturing	CRT tube manufacturing	Phosphorus (yellow or white)	Primary	0.32%

*Column may not add to 99% due to rounding.

3.3.10.2 Major contributors to the LCD water eutrophication impact results

Table 3-36 lists the materials that contribute to the top 99% of the LCD water eutrophication results. Like the CRT, the LCD water eutrophication indicator is driven by emissions from a single process group, in this case, LCD monitor/module manufacturing. Together, emissions of nitrogen and phosphorus from that process account for 94% of the total score. The LPG production process is the next largest contributor to the LCD water eutrophication score, where water releases of COD and ammonia ions account for more than 4% of the total.

Table 3-36. Top 99% to the LCD water eutrophication impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LCD monitor/module mfg.	Nitrogen	Primary	67%
Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	Primary	27%
Manufacturing	LPG production	COD	Secondary	3.4%
Manufacturing	LPG production	Ammonia ions	Secondary	0.88%
Manufacturing	LCD panel components	Phosphorus (yellow or white)	Primary	0.48%
Materials processing	PMMA sheet production	Ammonia	Secondary	0.40%

*Column may not add to 99% due to rounding.

3.3.10.3 Limitations and uncertainties

Eutrophication (nutrient enrichment) impacts are calculated from the mass of a chemical released directly to surface water and the chemical's eutrophication potential (EP). The EP is a partial equivalency factor derived from the ratio of nitrogen and phosphorus in the average composition of algae compared to the reference compound phosphate (see Section 3.1.2.9). As a partial equivalency approach, only a subset of substances can be converted into equivalency factors, which is a limitation of this LCIA methodology. However, the methodology does take into account nitrogen and phosphorus, which are the two major limiting nutrients of importance to eutrophication.

CRT water eutrophication results are dominated by LCI data from secondary sources, and are therefore subject to the limitations and uncertainties associated with secondary data. Furthermore, these results are ultimately due to the large amount of LPG reported to be used as a fuel in LPG glass production. Because of the large degree of variability in glass energy data received from three CRT glass manufacturers, CRT glass energy inputs are also uncertain and the subject of a sensitivity analysis (see Section 3.4). LCD results, on the other hand, are driven almost entirely by primary LCI data from the manufacturing life-cycle stage, which were collected to meet the goals, objectives, and temporal and geographic boundaries of the CDP and are therefore considered to be of better quality.

3.3.11 Water Quality

3.3.11.1 Biological oxygen demand (BOD)

Figure 3-14 presents the CRT and LCD LCIA results for the BOD water quality impacts category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.10. Complete results are listed in Tables M-25 (CRT) and M-26 (LCD) in Appendix M.

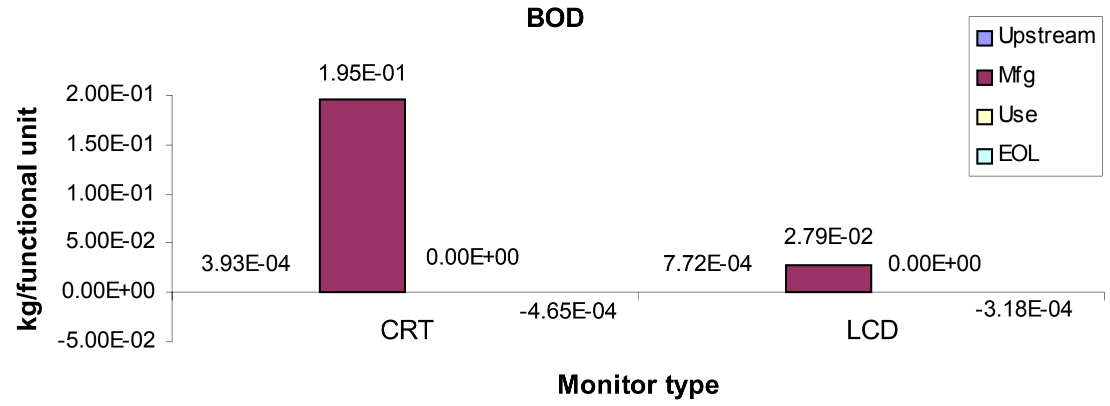

Figure 3-14. BOD impacts by life-cycle stage

During the life-cycle of a 17" CRT monitor, 0.195 kg of BOD are released to surface water. The life-cycle of a functionally equivalent 15" LCD results in 0.0283 kg of BOD surface water releases. As shown in Figure 3-14, BOD impacts for both monitor types are driven by surface water releases in the manufacturing stage, which contribute 100% of CRT impacts and 99% of LCD impacts. Note that small BOD impacts also occur in the upstream, materials processing life-cycle stage for both monitor types. These are almost entirely offset by negative BOD values at end of life due to the offset of electric grid emissions when the monitors are incinerated with energy recovery. Note also that there are no BOD emissions from the U.S. electric grid during the use stage. The incineration inventory is a secondary data set that contains a different electric grid inventory than the U.S. electric grid inventory developed by the CDP.

Table 3-37 lists the materials responsible for the top 99% of the CRT BOD impacts. CRT impacts in this category are driven by BOD releases from the LPG production process, most of which is used to make LPG employed as fuel in CRT glass manufacturing. BOD releases from CRT tube manufacturing also contribute a small percentage to the total score.

Table 3-37. Top 99% of the CRT BOD impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LPG production	BOD	Secondary	96%
Manufacturing	CRT tube manufacturing	BOD	Primary	3.3%

Table 3-38 lists the materials that contribute to the top 99% of the LCD BOD impacts. As shown in the table, LCD impacts are slightly more distributed among processes than CRT impacts, with BOD releases from four processes or process groups making up the list of top contributors. Note that BOD releases from LPG production (most of which is used to make LPG for LCD glass manufacturing) are much less for the LCD than the CRT, even though the LCD glass manufacturing inventory was derived from the CRT glass manufacturing inventory. This is because the CRT contains approximately ten times more glass than the LCD.

Table 3-38. Top 99% of the LCD BOD impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LCD monitor/module mfg.	BOD	Primary	61%
Manufacturing	LPG production	BOD	Secondary	32%
Manufacturing	LCD panel components	BOD	Primary	4.7%
Materials processing	Natural gas production	BOD	Secondary	0.99%

3.3.11.2 Total suspended solids (TSS)

Figure 3-15 presents the CRT and LCD LCIA results for the TSS water quality impacts category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.10. Tables M-27 and M-28 in Appendix M list complete results for the CRT and LCD, respectively.

The life-cycle TSS impact indicator is 0.874 kg of TSS for the CRT and 0.0615 kg of TSS for the LCD. TSS impacts for both monitor types are driven by the manufacturing stage, where 99 and 94% of impacts occur for the CRT and LCD, respectively. TSS impacts also occur in the upstream, materials processing life-cycle stage for both monitor types. Both technologies receive a credit on TSS impacts at EOL due to an offset of electric grid emissions when the monitors are incinerated with energy recovery.

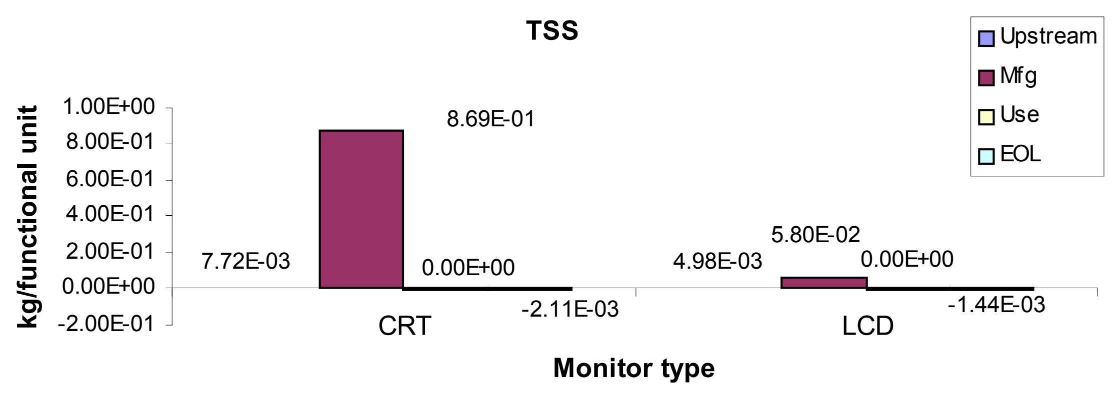

Figure 3-15. TSS impacts by life-cycle stage

Table 3-39 presents the major contributors to the CRT TSS indicator and lists the LCI data type. As with many other impact categories, the LPG production process is the single largest contributor to the CRT TSS indicator, accounting for 97% of the total score. Most of the LPG from this process is used as a fuel to produce CRT glass, but CRT energy inputs are uncertain and evaluated in a sensitivity analysis in Section 3.4. TSS surface water releases from the CRT glass/frit process group, CRT tube manufacturing, and fuel oil #6 production are also top contributors to the CRT TSS score. However, the contribution of these processes or process groups is small compared to that of the LPG production process.

Table 3-39. Top 99% of the CRT TSS impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LPG production	Suspended solids	Secondary	97%
Manufacturing	CRT glass/frit mfg.	Suspended solids	Primary	0.83%
Manufacturing	CRT tube manufacturing	Suspended solids	Primary	0.53%
Manufacturing	Fuel oil # 6 production	Suspended solids	Secondary	0.33%

Table 3-40 presents the top contributors to the LCD TSS impact score. Like the CRT results discussed above, TSS surface water releases from the LPG production process are responsible for the majority of LCD TSS impacts. LPG from this production process is used to produce LCD glass. Note that the actual mass of TSS releases from the LCD-related process is much smaller than those from the CRT-related process. This is because the LCD only uses about 10% as much glass as the CRT. TSS releases from the LCD monitor/module process group also account for a sizeable percentage of LCD TSS impacts.

Table 3-40. Top 99% of the LCD TSS impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	Suspended solids	Secondary	66%
Manufacturing	LCD monitor/module mfg.	Suspended solids	Primary	25%
Materials processing	PMMA sheet production	Suspended solids	Secondary	2.2%
Materials processing	Natural gas production	Suspended solids	Secondary	2.0%
Materials processing	Steel production, cold-rolled, semi-finished	Suspended solids	Secondary	1.6%
Materials processing	Aluminum production (all virgin)	Suspended solids	Secondary	1.1%
Manufacturing	LCD panel components	Suspended solids	Primary	1.0%

*Column may not add to 99% due to rounding.

3.3.11.3 Limitations and uncertainties

Both BOD and TSS indicators are calculated using a loading approach (i.e., the impact score is based on the inventory amounts) and are therefore highly sensitive to inventory data quality. CRT impact results are driven almost entirely by the LPG production inventory (a secondary data set) and are therefore subject to the limitations and uncertainties associated with secondary data. In particular, see Section 3.3.2.3 for a detailed discussion of LPG production data quality. In addition, note that LPG production impacts are almost all due to the large amount of LPG reported to be used as a fuel in CRT glass manufacturing. As note previously, CRT glass energy inputs are uncertain and are evaluated in a sensitivity analysis (see Section 3.4).

LCD impact results, on the other hand, are driven by LCI data from both primary and secondary sources and are therefore considered to be of somewhat better quality than the CRT results. However, a significant percentage of LCD water quality impacts also come from the large amount of LPG used as a fuel input to LCD glass manufacturing. These energy inputs are also uncertain and are evaluated in the sensitivity analysis in Section 3.4.

3.3.12 Radioactivity

Figure 3-16 presents the CRT and LCD LCIA results for the radioactivity impact category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.11. Complete CRT and LCD results are presented in Tables M-29 and M-30 in Appendix M, respectively.

The life-cycle radioactivity indicator is 38.5 million Bequerels (Bq) for the CRT and 12.2 million Bq for the LCD. Radioactivity impacts are driven by radioactive emissions from the upstream, materials processing stage for both monitor types, which contributes 99% of CRT life-cycle impacts and 98% of LCD life-cycle impacts. This result was unforeseen, since one might expect the majority of radioactive emissions to occur from the use stage, due to electricity generation at nuclear power plants. As it turns out, radioactivity impacts are being driven by data for nuclear fuel reprocessing that are included in the electric grid inventories for the steel, invar (an alloy of nickel and ferrite), and ferrite production process groups.

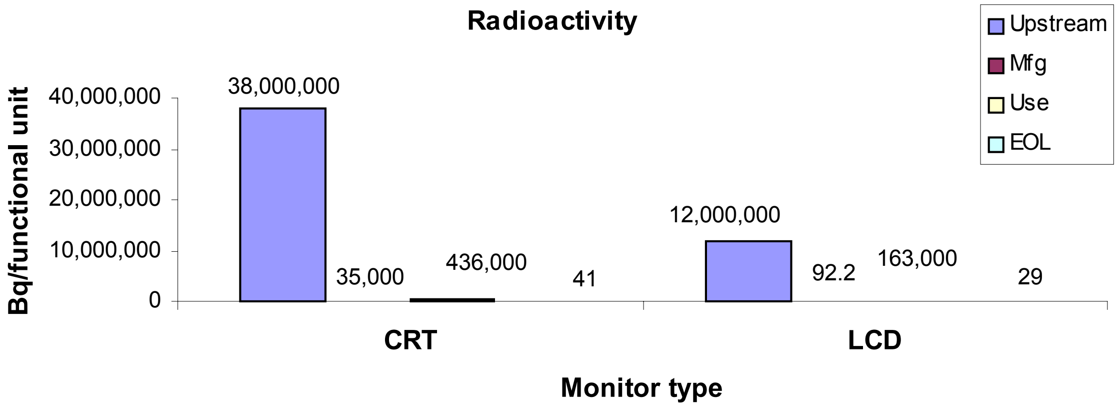

Figure 3-16. Radioactivity impacts by life-cycle stage

The LCIs for steel, invar, and ferrite were obtained from two databases developed by the former *Ecobilan Group,* an LCA consulting firm that was previously headquartered in France (see Section 2.2.1.1 for a discussion of how these databases were selected). Per *Ecobilan*, the ferrite inventory contains older data that may include radioactive emissions from electricity use. For the steel and nickel inventories, the source of both is site data in Europe, with the radioactive emissions coming from electricity in Europe, where nuclear fuel is reprocessed. In fact, the electricity data are from France for both materials, and France is one of the few countries (including Japan and the United Kingdom) that reprocesses nuclear fuel (Glazebrook, 2001). Therefore, the radioactivity impacts calculated from these inventories are more representative of impacts from countries that reprocess nuclear fuel than impacts from countries that do not.

To further illustrate this point, Tables 3-41 and 3-42 lists the materials and process groups that contribute to the top 99% of the CRT and LCD radioactivity indicator results, respectively. As shown in the tables, radioactivity impacts for both monitor types are driven by releases of plutonium-241 from steel (both monitor types), invar (CRT), and ferrite (CRT) production. Plutonium-241 is a byproduct of fuel reprocessing. Xenon -133 releases from the U.S. electric grid contribute slightly to the LCD radioactivity impacts and to a lesser degree to the CRT total impacts. Note that the actual amount of radioactivity from Xenon-133 is greater for the CRT than the LCD, but contributes a smaller percent of total impacts.

Table 3-41. Top 99% of the CRT radioactivity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Steel production, cold-rolled, semi-finished	Plutonium-241 (isotope)	Secondary	62%
Materials processing	Invar	Plutonium-241 (isotope)	Secondary	18%
Materials processing	Ferrite	Plutonium-241 (isotope)	Secondary	17%
Use	U.S. electric grid	Xenon-133 (isotope)	Model/secondary	0.81%
Materials processing	Steel production, cold-rolled, semi-finished	Plutonium-240 (isotope)	Secondary	0.27%
Materials processing	Steel production, cold-rolled, semi-finished	Cesium-135 (isotope)	Secondary	0.24%

*Column may not add to 99% due to rounding.

Table 3-42. Top 99% of the LCD radioactivity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Steel production, cold-rolled, semi-finished	Plutonium-241 (isotope)	Secondary	96%
Use	U.S. electric grid	Xenon-133 (isotope)	Model/secondary	0.95%
Manufacturing	Japanese electric grid	Xenon-133M (isotope)	Secondary	0.54%
Materials processing	Steel production, cold-rolled, semi-finished	Plutonium-240 (isotope)	Secondary	0.42%
Materials processing	Steel production, cold-rolled, semi-finished	Cesium-135 (isotope)	Secondary	0.38%

*Column may not add to 99% due to rounding.

Most of the radioactivity impacts are based on LCI data from secondary sources and are therefore subject to the limitations and uncertainties in secondary data, discussed previously. In addition, because radioactivity impacts are being driven by radioactive emissions from fuel reprocessing in France, they may not be representative of radioactivity impacts elsewhere. However, most of the CRT and LCD primary manufacturing data were collected from companies in Japan, where fuel reprocessing also occurs. For example, if Japanese CRT and LCD monitor and/or components manufacturers purchase steel from Japanese steel mills, the radioactivity emissions from electricity used to manufacture the steel could be similar. Japan ranked second in worldwide steel production in 2000 behind Mainland China, and third in 1999 behind Mainland China and the United States (IISI, 2001).

Note that the Japanese electric grid, which is linked to CRT and LCD production inventories, was developed from the U.S. electric grid inventory and therefore does not account for radioactive emissions from fuel reprocessing. This means that radioactive impacts from Japanese manufacturing processes that consume electricity are understated. For example, electricity used in the CRT glass/frit process group was the ninth largest contributor to the CRT energy use score, but the inventory for this process group does not account for fuel reprocessing emissions.

3.3.13 Potential Human Health Impacts

As discussed in Section 3.1.2.12, human health impacts included in the scope of this LCA are chronic (repeated dose) effects, including non-carcinogenic and carcinogenic effects to both workers and the public, and aesthetics. (Although not a health effect *per se*, aesthetics pertains to human welfare.)

Chronic health effect (cancer and noncancer) impacts are calculated using the scoring of inherent properties approach where an impact score is based on the inventory amount weighed by a hazard value (HV). The HV represents the chronic toxicity of a specific material (see Table K-8 in Appendix K for a list of toxicity values used to calculate hazard values). In this manner the inventory amount (the toxic chemical input amount for occupational health effects, and the output amount for public health effects) is used as a surrogate for exposure, while the hazard value represents the inherent toxicity of the chemical for chronic exposure.

The CDP human health effects LCIA methodology does not consider the fate and transport of a toxic chemical in the environment, nor does it evaluate the potential for actual exposures to occur. LCI data do not have the temporal and spatial specificity needed to estimate potential dose rates, for example, nor do they contain information on engineering controls used in an occupational setting to reduce exposure. [It should be noted that more sophisticated models for evaluating human health effects in an LCA framework are being developed that use a multimedia fate, multi-pathway human exposure, and toxicological potency approach (Bare, 1999). However, such models are less comprehensive in terms of the number of chemicals for which there are data.] The limitations and uncertainties in the health effects scores are discussed further below, following the presentation of results.

3.3.13.1 Chronic occupational health effects

Figure 3-17 presents the CRT and LCD LCIA results by life-cycle stage for the chronic occupational health effects impact category, based on the impact assessment methodology presented in Section 3.1.2.12. Complete CRT and LCD results are presented in Tables M-31 and M-32 in Appendix M.

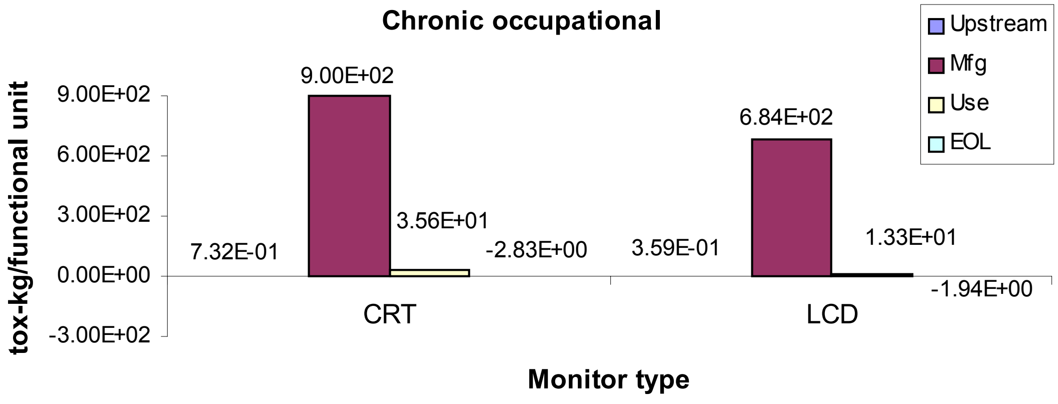

Figure 3-17. Chronic occupational impacts by life-cycle stage

The life-cycle chronic occupational health effects indicator is 934 tox-kg per functional unit for the CRT, and 696 tox-kg per functional unit for the LCD. As shown in the figure, the total score is dominated by toxic chemical inputs to the manufacturing stage, which account for 98% and 96% of CRT and LCD impacts in this category, respectively. This result was expected since inputs to the other life-cycle stages tend to be raw materials (e.g., ores, coal, etc., for the materials processing and use life-cycle stages) or finished products (e.g., the monitors themselves for the EOL stage) that are not classified as toxic materials (see Table K-9 in Appendix K for a l

list of materials excluded from the toxic classification). Both the CRT and LCD receive negative chronic occupational health effects scores at end of life due to the offset of electric grid emissions when the monitors are incinerated with energy recovery.

Table 3-43 lists the materials responsible for the top 99% of the CRT chronic occupational health effects score and the LCI data type. LCI data for most of the top contributors are primary data collected from manufacturers by the CDP. In general, these data are expected to be of better quality (for the purposes of the CDP) than data from secondary sources, since they were collected to meet the goals and scope of the CDP.

Table 3-43. Top 99% of the CRT chronic occupational health effects score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	CRT glass/frit mfg.	Liquified petroleum gas	Primary	75%
Manufacturing	PWB manufacturing	Sulfuric acid	Primary	13%
Manufacturing	CRT tube manufacturing	Sulfuric acid	Primary	4.1%
Use	U.S. electric grid	Natural gas	Model/secondary	3.0%
Manufacturing	CRT glass/frit mfg.	Barium carbonate	Primary	1.8%
Use	U.S. electric grid	Petroleum (in ground)	Model/secondary	0.81%
Manufacturing	CRT tube manufacturing	Fuel oil # 6	Primary	0.79%

*Column may not add to 99% due to rounding.

LPG inputs to the glass/frit process group, primarily from CRT glass manufacturing, contribute 75% of the CRT impacts in this category. The high impact score for LPG is mainly due to the large amount of LPG inputs to the glass/frit process group (351 kg/functional unit), which results in a high score when multiplied by the HV. No toxicity data were available for LPG. Therefore, it was assigned default HVs of one for both cancer and noncancer effects (total HV=2), representative of mean cancer and noncancer toxicity values. As noted previously, glass manufacturing energy data are uncertain and therefore evaluated in a sensitivity analysis (see Section 3.4).

Sulfuric acid used in PWB manufacturing is the next greatest contributor to the CRT chronic occupational health effects results (13%) followed by sulfuric acid used in CRT tube manufacturing (4.1%). The sulfuric acid HV is based on an inhalation NOAEL of 0.1 mg/m^3, which is significantly lower (and therefore more toxic) than the geometric mean inhalation NOAEL of 68.7 mg/m^3. Consequently, sulfuric acid impacts are driven more by its inherent toxicity for noncancer effects than the input amounts (0.18 kg per functional unit for PWB manufacturing and 0.056 kg per functional unit for CRT tube manufacturing). Sulfuric acid has no cancer slope factor and an IARC weight of evidence (WOE) classification of 3 (not classifiable for carcinogenicity), and therefore received an HV of zero for cancer effects.

Natural gas and petroleum used as fuels in the U.S. electric grid, barium carbonate used in the CRT glass/frit process group and fuel oil #6 used to manufacture the CRT tube round out the top contributors to the CRT chronic occupational health effects score. Barium carbonate has no cancer slope factor and an EPA cancer WOE of D (not classifiable), and therefore has an HV of zero for cancer effects. However, its oral NOAEL is 0.21 mg/kg-day compared to the geometric mean oral NOAEL of 11.9 mg/kg-day, which results in an HV of 57 for noncancer effects. Therefore, like sulfuric acid, the barium carbonate impacts are driven more by its inherent toxicity than the input amount (0.297 kg per functional unit). No specific toxicity data were available for natural gas, petroleum, or fuel oil #6; consequently they were assigned a default HV of one for both cancer and noncancer effects (total HV=2).

Table 3-44 lists the materials that contribute to the top 99% of the LCD chronic occupational health effects score. Like the CRT, LCI data for most of the top contributors are primary data collected from manufacturers by the CDP, and are therefore expected to be of generally better quality (for the purposes of the CDP) than data from secondary sources.

Table 3-44. Top 99% of the LCD chronic occupational health effects score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LCD monitor/module mfg.	Liquified natural gas	Primary	57%
Manufacturing	LCD monitor/module mfg.	Sulfuric acid	Primary	23%
Manufacturing	PWB manufacturing	Sulfuric acid	Primary	8.0%
Manufacturing	LCD glass manufacturing	Liquified petroleum gas	Primary	4.7%
Manufacturing	LCD monitor/module mfg.	Phosphine	Primary	1.8%
Manufacturing	LCD panel components	Sulfuric acid	Primary	1.6%
Use	U.S. electric grid	Natural gas	Model/secondary	1.5%
Manufacturing	LCD monitor/module mfg.	Dimethylsulfoxide	Primary	1.1%
Manufacturing	LCD monitor/module mfg.	Ethanolamine	Primary	0.62%

*Column may not add to 99% due to rounding.

As shown in the table, LCD impacts in this category are dominated by LNG used in LCD monitor/module manufacturing. The high impact score for LNG is primarily due to the large amount of ancillary LNG inputs (194 kg/functional unit) in the LCD monitor/module manufacturing inventory, which results in a high score when multiplied by the HV. No toxicity data were available for LNG. Therefore, it was assigned a default, mean HV of one for both cancer and noncancer effects (total HV=2). As noted previously, only one of seven LCD module/monitor manufacturers reported using LNG as an ancillary material. Therefore, the total score for LCD chronic occupational health effects may not be representative of the industry as a whole. If we remove this application of LNG from the LCD inventory, the LCD occupational health effects result is reduced by 58 percent, from 683 tox-kg per monitor to 288 tox-kg per monitor. Note, however that other LCD monitor/module manufacturers did report using LNG as a fuel.

Sulfuric acid used in three process groups (LCD module/monitor manufacturing, PWB manufacturing, and LCD panel components) accounts for another 33% of the LCD chronic occupational health effects score. As discussed above for the CRT, sulfuric acid has a relatively low toxicity value, and therefore a high HV, which results in a high impact score for a small input amount. The LCD module/monitor manufacturing process group has the highest impact score for sulfuric acid because it has the greatest input amount (0.229 kg per functional unit).

The remaining top contributors to the LCD chronic occupational health effects score are LPG used in LCD glass manufacturing; and phosphine, dimethylsulfoxide, and ethanolamine used in LCD monitor/module manufacturing; and natural gas used as a fuel by the U.S. electric grid. As discussed earlier, LCD glass energy inputs are uncertain and evaluated in a sensitivity analysis in Section 3.4. The LPG score is based on default HVs (representative of the geometric mean toxicity values) for both cancer and noncancer effects, since no toxicity data were available for LPG.

The phosphine score is driven by its low oral NOAEL value (0.026 mg/kg-day), which is significantly lower than the geometric mean value of 68.7 mg-kg-day. Thus, due to its inherently high toxicity, a relatively small input of phosphine (in this case, 0.027 kg per functional unit) results in a relatively high chronic occupational health effects score. No slope factors or cancer WOE classifications were found for phosphine, indicating a default HV of one was used, which is far outweighed by the non-cancer hazard value.

Dimethylsulfoxide is less toxic than phosphine (oral LOAEL =1.0 mg/kg-day), but has a greater input amount (0.066 kg per functional unit). However, phosphine's greater toxicity outweighs the greater input amount for dimethylsulfoxide, resulting in a higher impact score for phosphine.

No specific toxicity data were available for natural gas; consequently it was assigned a default HV of one for both cancer and noncancer effects (total HV=2).

3.3.13.2 Chronic public health effects

Figure 3-18 presents the CRT and LCD LCIA scores by life-cycle stage for the chronic public health effects category, based on the impact assessment methodology presented in Section 3.1.2.12. Complete results are presented in Tables M-33 and M-34 in Appendix M, respectively.

The life-cycle chronic public health effects score is 1,980 tox-kg per functional unit for the CRT and 902 tox-kg per functional unit for the LCD. As shown in the figure, the CRT score is dominated by toxic chemical outputs from electricity generation in the use stage, which

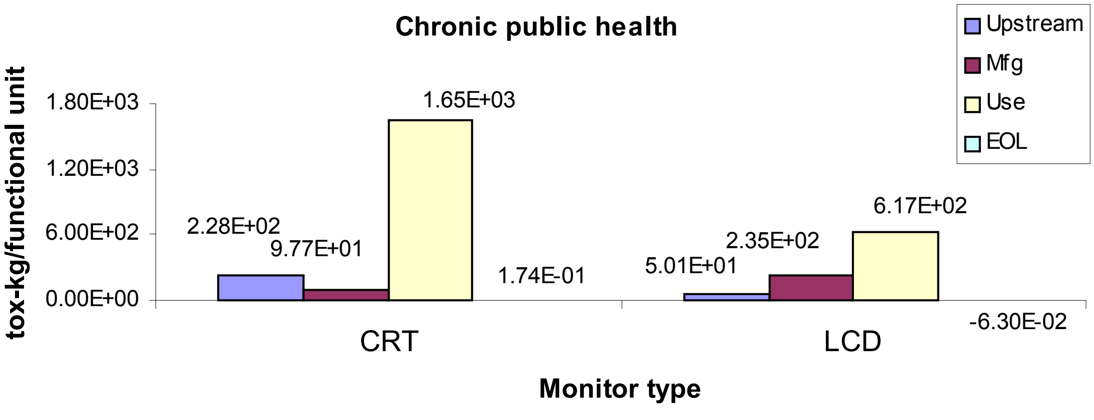

Figure 3-18. Chronic public health impacts by life-cycle stage

account for almost 84% of CRT impacts in this category. To a lesser degree, LCD chronic public health effect impacts are also driven by emissions from electricity generation in the use stage, which account for more than 68% of the total. Note that the ratio of CRT to LCD use stage public health impacts is the same as the ratio of CRT to LCD use stage electricity consumption (634 kWh/life for the CRT to 237 kWh/life for the LCD).

The materials processing stage contributes almost 12% of CRT chronic public health effect impacts and almost six percent of LCD impacts. The manufacturing life-cycle stage is responsible for five and 26% of CRT and LCD impacts in this category, respectively. Both monitors receive very small public chronic health effects scores at end of life. This is because most public health effect impacts from CRT and LCD recycling and disposal processes are offset by a credit on electric grid emissions when the monitors are incinerated with energy recovery.

Table 3-45 presents the materials that contribute to the top 99% of the CRT chronic public health effects score. As shown in the table, SO_2 emissions from a number of different process groups almost completely dominate CRT impacts in this category, accounting for more than 98% of the total. All of the SO_2 LCI data shown in the table are either from secondary data sets not developed specifically for the CDP, or from the electric grid inventories developed from secondary sources for this project. Sulfur dioxide has a relatively high HV based on an inhalation NOAEL of 0.104 mg/m^3, compared to the geometric mean inhalation NOAEL of 68.7 mg/m^3. In addition, from a mass loading perspective, SO_2 emissions were the second largest contributor to CRT life-cycle air pollutant emissions, exceeded only by emissions of carbon dioxide (CO_2). Carbon dioxide is not classified as toxic, and therefore does not contribute to the human health effects scores.

Table 3-45. Top 99% of the CRT chronic public health effects score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	83%
Materials processing	Invar	Sulfur dioxide	Secondary	8.3%
Manufacturing	Japanese electric grid	Sulfur dioxide	Model/secondary	2.9%
Manufacturing	U.S. electric grid	Sulfur dioxide	Model/secondary	1.3%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur dioxide	Secondary	1.3%
Materials processing	Aluminum production	Sulfur dioxide	Secondary	0.70%
Materials processing	Polycarbonate production	Sulfur dioxide	Secondary	0.40%
Manufacturing	LPG production	Carbon monoxide	Secondary	0.29%
Materials processing	Lead production	Sulfur dioxide	Secondary	0.23%

*Column may not add to 99% due to rounding.

Most of the sulfur dioxide emissions that contribute to the CRT chronic public health effects score are from the combustion of fossil fuels used to generate electricity. For example, the electricity required to power the monitor during the use stage accounts for the vast majority of SO_2 emissions and 83% of the CRT chronic public health effects score. Sulfur dioxide emissions from electricity consumed in the United States and Japan during the manufacturing life-cycle stage account for another 4.2% of the total score. Much of the SO_2 emissions reported in secondary data sets for the materials processing life-cycle stage may also be from electricity generation since many of these data also contain an electric grid inventory.

Table 3-46 lists the materials that contribute to the top 99% of the LCD chronic public health effects score and the LCI data type. LCD impacts in this category are also dominated by SO_2 emissions, which are responsible for roughly 93% of impacts. Like the CRT, most of these emissions occur from electricity generation, either during the use stage (68%) or manufacturing (21%). As noted previously, SO_2 has a relatively high HV due to its low toxicity value (inhalation NOAEL = 0.104 mg/m^3). Similar to the CRT, from a mass loading perspective, SO_2 emissions were the second largest contributor to LCD life-cycle air pollutant emissions, exceeded only by emissions of CO_2.

Table 3-46. Top 99% of the LCD chronic public health effects score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	68%
Manufacturing	Japanese electric grid	Sulfur dioxide	Model/secondary	21%
Manufacturing	LCD monitor/module mfg.	Phosphine	Primary	3.2%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur dioxide	Secondary	1.4%
Materials processing	PMMA sheet production	Sulfur dioxide	Secondary	0.96%
Materials processing	Natural gas production	Methane	Secondary	0.78%
Materials processing	Natural gas production	Benzene	Secondary	0.59%
Materials processing	Aluminum production	Sulfur dioxide	Secondary	0.57%
Materials processing	Natural gas production	Carbon monoxide	Secondary	0.53%
Materials processing	Polycarbonate production	Sulfur dioxide	Secondary	0.49%
Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	Primary	0.38%
Manufacturing	U.S. electric grid	Sulfur dioxide	Model/secondary	0.35%

*Column may not add to 99% due to rounding.

Other top contributors to the LCD chronic public health effects score include phosphine and phosphorus from LCD monitor/module manufacturing, and methane, benzene, and carbon monoxide from natural gas production. As noted above in the section on chronic occupational health effects, the phosphine score is driven by its low oral NOAEL value (0.026 mg/kg-day), which is significantly lower than the geometric mean value of 68.7 mg-kg-day, resulting in a high HV. Thus, a relatively small output of phosphine (in this case, air emissions of 0.063 kg per functional unit) results in a relatively high chronic public health effects score.

The benzene and phosphorus chronic health effects scores are also driven more by their toxicity than the output amounts. Benzene is a known human carcinogen (EPA WOE Class A) that also causes noncancer health effects. The HV for benzene is based on its oral slope factor [0.055 $(\text{mg/kg-day})^{-1}$] and its inhalation NOAEL for noncancer effects (1.15 mg/m^3), which together result in a high HV. (Benzene also has an *inhalation* slope factor and an *oral* NOAEL value, but these yield lower hazard values when compared to the geometric mean values.)

Phosphorus has an EPA WOE classification of D (not classifiable as to human carcinogenicity), but has a low oral NOAEL value (0.015 mg/kg-day), which also gives it a high HV.

No toxicity data were available for methane. Therefore, it received a default HV of one for both cancer and noncancer effects (HV=2 total). The HV for carbon monoxide is based on an inhalation LOAEL of 55 mg/m^3.

3.3.13.3 Chronic public health effect scores modified to exclude sulfur dioxide

Because the chronic public health effects scores for both the CRT and the LCD are dominated by SO_2 emissions, a secondary analysis was run to identify the top contributors to public health impacts when SO_2 emissions are excluded from the inventories. Results of this analysis may be more useful to manufacturers seeking to identify problematic toxic chemicals within their own manufacturing processes.

Figure 3-19 presents the CRT and LCD chronic public health effects scores by life-cycle stage when SO_2 emissions are excluded from the inventories. Under this scenario, the CRT score is reduced almost 99% from 1980 tox-kg to 26 tox-kg per functional unit, and the LCD score is reduced about 93% from 902 tox-kg to 61 tox-kg per functional unit. Note that these scores should not be used to evaluate which monitor type has higher overall impacts in this category, but they are useful for identifying life-cycle improvement opportunities that were previously obscured by SO_2 impacts.

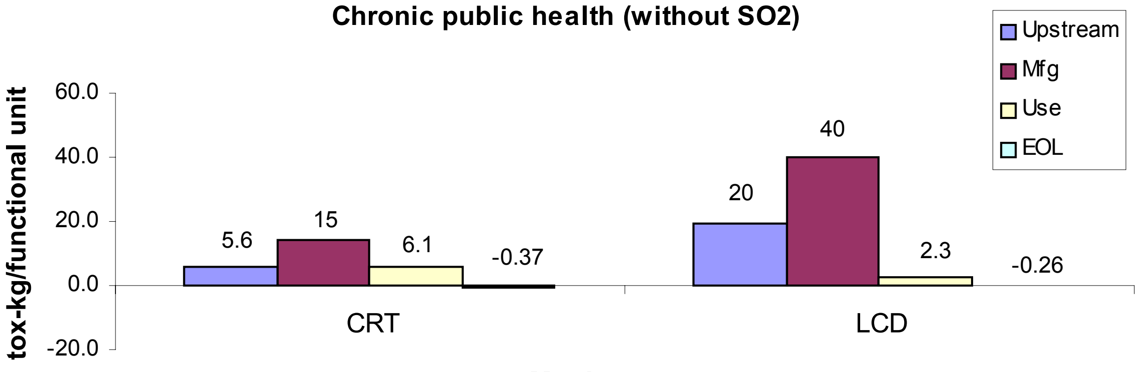

Figure 3-19. Chronic public health impacts (without SO2) by life-cycle stage

With SO_2 emissions removed from the inventories, chronic public health effect impacts are highest in the manufacturing life-cycle stage for both the CRT (56% of impacts) and the LCD (65% of impacts). The use stage is the next largest contributor for the CRT (22%), and the materials processing stage in the next largest contributor for the LCD (32%). As will be shown below, use stage impacts are significant for the CRT, even when SO_2 emissions are excluded, because of the CRT's relatively high electricity consumption during use by the consumer and the associated emissions of pollutants from U.S. power plants.

Table 3-47 presents the materials that contribute greater than one percent of CRT impacts when SO_2 emissions are excluded from the CRT inventory. Under this scenario, CRT chronic public health impacts are still being driven by emissions of criteria air pollutants,[2] including carbon monoxide, nitrogen oxides, and sulfur oxides (assuming that SO_2 emissions comprise a large part of the sulfur oxide emissions shown in the table). As shown in the table, emissions of these three pollutants or pollutant categories are responsible for some 48% of CRT chronic public health impacts when pure SO_2 emissions are excluded from the CRT inventory. Note that the majority of these emissions occur from the LPG production process, and most of this LPG is used as a fuel in CRT glass manufacturing. CRT glass manufacturing energy inputs are uncertain and evaluated in a sensitivity analysis (See Section 3.4). Other significant contributors include arsenic from lead production, methane from LPG production and the U.S. electric grid inventory, vanadium and benzene from LPG production, and titanium tetrachloride from aluminum production.

Table 3-47. Materials contributing greater than 1% of the CRT chronic public health effects score (without SO_2)

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LPG production	Carbon monoxide	Secondary	22.35%
Use	U.S. electric grid	Nitrogen oxides	Modeled/secondary	9.12%
Materials processing	Lead	Arsenic	Secondary	8.55%
Manufacturing	LPG production	Methane	Secondary	6.50%
Manufacturing	LPG production	Sulfur oxides	Secondary	6.21%
Use	U.S. electric grid	Methane	Modeled/secondary	4.99%
Manufacturing	LPG production	Nitrogen oxides	Secondary	4.44%
Use	U.S. electric grid	Carbon monoxide	Modeled/secondary	4.23%
Manufacturing	LPG production	Vanadium	Secondary	4.05%
Manufacturing	LPG production	Benzene	Secondary	3.32%
Materials processing	Aluminum production (virgin)	Titanium tetrachloride	Secondary	2.79%
Manufacturing	CRT glass/frit mfg.	Fluorides (F-)	Primary	2.27%
Use	U.S. electric grid	Arsenic	Modeled/secondary	2.16%
Use	U.S. electric grid	Hydrochloric acid	Modeled/secondary	1.91%
Materials processing	Steel Prod., cold-rolled, semi-finished	Carbon monoxide	Secondary	1.16%

Table 3-48 presents the materials that contribute greater than one percent of LCD impacts when SO_2 emissions are excluded from the LCD inventory. Under this scenario, phosphine emissions from LCD monitor/module manufacturing are the dominant factor in the LCD chronic public health effects score, contributing 47% of the total. Other significant contributors include methane, benzene, carbon monoxide, and nitrogen oxides from natural gas production, and phosphorus, fluorides, tetramethyl ammonium hydroxide, and nitrogen oxides from LCD monitor/module manufacturing. Recall that the LCD monitor/module manufacturing process

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[2] The criteria air pollutants are those for which U.S. National Ambient Air Quality Standards have been adopted. They are carbon monoxide, lead, nitrogen oxides, ozone, particulate matter, and sulfur dioxide.

consumes the majority of the natural gas made in the natural gas production process, where LNG is used as an ancillary material. However, only one of the seven LCD monitor/module manufacturers that provided inventory data to the CDP reported the ancillary use of LNG. Other LCD monitor/module manufactures did report the use of LNG as a fuel.

Table 3-48. Materials contributing greater than 1% of the LCD chronic public health effects score (without SO_2)

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LCD monitor/module mfg.	Phosphine	Primary	46.7%
Materials processing	Natural gas production	Methane	Secondary	11.4%
Materials processing	Natural gas production	Benzene	Secondary	8.61%
Materials processing	Natural gas production	Carbon monoxide	Secondary	7.81%
Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	Primary	5.56%
Manufacturing	LCD monitor/module mfg.	Fluorides (F-)	Primary	4.15%
Materials processing	Natural gas production	Nitrogen oxides	Secondary	2.12%
Manufacturing	LCD monitor/module mfg.	Tetramethyl ammonium hydroxide	Primary	2.09%
Manufacturing	LCD monitor/module mfg.	Nitrogen oxides	Primary	1.78%
Use	U.S. electric grid	Nitrogen oxides	Modeled/secondary	1.43%

3.3.13.4 Limitations and uncertainties: chronic human health effects

Most of the limitations and uncertainties in the chronic human health effects results presented here can be grouped into three categories:

1. *Structural or modeling limitations and uncertainties* associated with the accuracy of the toxic chemical classification method and the chemical scoring approach used to characterize human health effects.
2. *Toxicity data limitations and uncertainties* associated with the availability and accuracy of toxicity data to represent potential human health effects.
3. *LCI data limitations and uncertainties* associated with the accuracy and representativeness of the inventory data.

Each of these are discussed below.

Structural or modeling limitations and uncertainty. The chemical scoring method used in the human health effects impact characterization is a screening tool to identify chemicals of potential concern, not to predict actual effects or characterize risk. A major limitation in the method is that it only measures relative toxicity, combined with inventory amount. It does not take chemical fate, transformation, or degradation into account. In addition, it uses a simple surrogate value (i.e., inventory amount) to evaluate the potential for exposure, when actual exposure potential involves many more factors, some of which are chemical-specific. Other sources of uncertainty include possible omissions by the CDP researchers in the impact classification process (e.g., potentially toxic chemicals not classified as such) or misrepresentation of chemicals in the impact characterization method itself (e.g., misrepresenting a chemical as a small contributor to total impacts, because of missing or inaccurate toxicity data). Some of these limitations and uncertainties may also be considered limits in the toxicity data which are discussed further below.

It should also be noted, however, that because LCA involves analyzing many processes over the entire life cycle of a product, a comprehensive, quantitative risk assessment of each chemical input or output can not be done. Rather, LCA develops relative impacts that often lack temporal or spatial specificity, but can be used to identify materials for more detailed evaluation. More detailed assessments of the toxicity and potential exposures to selected materials are performed in Chapter 4.

Toxicity data limitations and uncertainties. Major uncertainties in the impact assessment for potentially toxic chemicals result from missing toxicity data and from limitations of the available toxicity data. Uncertainties in the human health hazard data (as typically encountered in a hazard assessment) include the following:

- Using dose-response data from laboratory animals to represent potential effects in humans.
- Using data from homogeneous populations of laboratory animals or healthy human populations to represent the potential effects on the general human populations, with a wide range of sensitivities.
- Using dose-response data from high dose toxicity studies to represent potential effects that may occur at low levels.
- Using data from short-term studies to represent the potential effects of long-term exposures.
- Assuming a linear dose-response relationship.
- Possibly increased or decreased toxicity resulting from chemical interactions.

Regarding uncertainties resulting from missing toxicity data, there is uncertainty associated with using a default HV (i.e., assuming average toxicity for that measure when a chemical could be either more or less toxic than average). However, the use of neutral default values for missing data reduces the bias that typically favors chemicals with little available information. Use of a data-neutral default value to fill data gaps is consistent with principles for chemical ranking and scoring (Swanson and Socha, 1997). Of the 273 chemicals classified as potentially toxic in the CDP LCA, 156 (57%) had no toxicity data for carcinogenic effects and 128 (47%) had no data for noncarcinogenic effects. Ninety-seven chemicals (36%) had no human health toxicity data whatsoever.

LCI data limitations and uncertainty. Limitations and uncertainties in the LCI data have been discussed previously and are generally related to: (1) uncertainties in data from secondary sources that may not be representative of the geographic and temporal boundaries of this LCA, and (2) uncertainties in a few of the primary data points collected specifically for this project. With regard to the latter, glass manufacturing energy inputs are particularly uncertain despite numerous attempts to resolve the uncertainty, but are responsible for a significant portion of CRT human health impacts. Glass manufacturing energy inputs are evaluated in a sensitivity analysis in Section 3.4. The amount of LNG used as an ancillary material in LCD monitor/module manufacturing is also uncertain (also despite attempts to resolve questions regarding the data), but this material contributes a significant portion of LCD occupational health impacts. As noted previously, removing this application of LNG from the LCD monitor/module manufacturing inventory would reduce the LCD chronic occupational health effects score by 68%.

3.3.13.5 Aesthetic impacts (odor)

Figure 3-20 presents the CRT and LCD LCIA results for the aesthetic impacts (odor) category, based on the impact assessment methodology presented in Section 3.1.2.12. Complete results for the CRT and LCD are presented in Tables M-35 and M-36 in Appendix M, respectively. The life-cycle aesthetic (odor) impact result is 7.58 million m^3 malodorous air per functional unit for the CRT and 5.04 million m^3 malodorous air per functional unit for the LCD. As shown in the figure, this impact category indicator is dominated by air emissions in the manufacturing stage for both the CRT (96% of total) and the LCD (98% of total). Both monitor types receive relatively minor contributions in the use and materials processing life-cycle stages, and negative values at end of life. Negative values are due to the offset of electric power plant emissions from incineration with energy recovery.

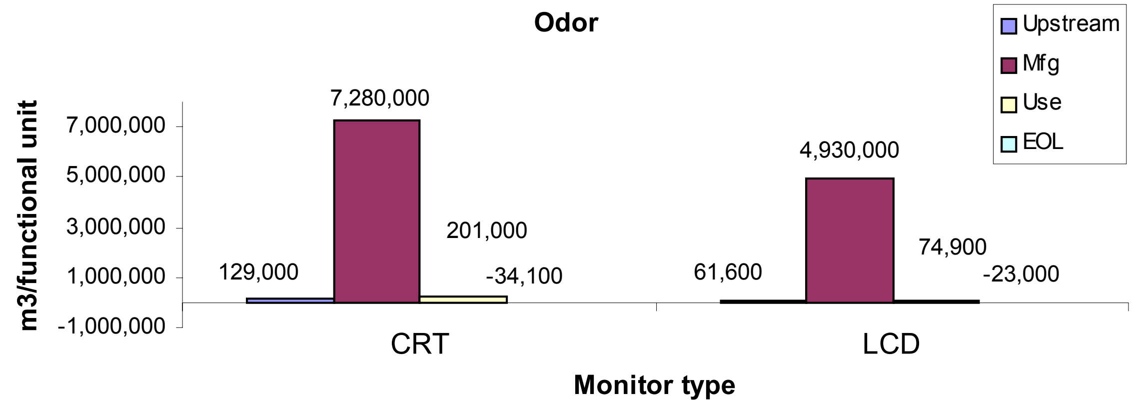

Figure 3-20. Odor impacts by life-cycle stage

Major Contributors to the CRT Aesthetics (Odor) Result

Table 3-49 lists the materials that contribute to the top 99% of the CRT aesthetic impacts result and the LCI data type. Air emissions of hydrogen sulfide from LPG production in the manufacturing life-cycle stage dominate the CRT odor impacts, contributing 94% of the total score. Hydrogen sulfide impacts are calculated based on an odor threshold value (OTV) of 0.00043 mg/m^3. [See Table K-7 in Appendix K for a list of OTVs used to calculate aesthetic (odor) impacts.] As noted previously, most of the LPG produced by this process is used as a fuel in CRT glass manufacturing, but glass manufacturing energy inputs are uncertain. The next largest contributor to the CRT is acetaldehyde emitted from the U.S. electric grid during the use stage. Acetaldehyde has a lower OTV (0.00027 mg/m^3) than LPG, and is also emitted in smaller quantities. Emissions of hydrogen sulfide from fuel oil #6 production, steel production, and ABS production are the remaining top contributors to the CRT aesthetic impacts score. LCI data for all of the top contributors are either from secondary data sets or developed by CDP researchers from secondary sources.

Table 3-49. Top 99% of the CRT aesthetic (odor) impacts score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	Hydrogen sulfide	Secondary	94%
Use	U.S. electric grid	Acetaldehyde	Model/secondary	2.5%
Manufacturing	Fuel oil #6 production	Hydrogen sulfide	Secondary	0.98%
Materials processing	Steel production, cold-rolled, semi-finished	Hydrogen sulfide	Secondary	0.42%
Materials processing	ABS production	Hydrogen sulfide	Secondary	0.31%

*Column may not add to 99% due to rounding.

Major Contributors to the LCD Aesthetics (Odor) Result

Table 3-50 presents the materials that contribute to the top 99% of the LCD aesthetics impact score and the LCI data type. LCD impacts are dominated by air emissions of phosphine from LCD monitor/module manufacturing, which contribute 89% of the total score. OTVs reported for phosphine range from 0.014 to 2.8 mg/m^3. The lower, more sensitive value (0.014 mg/m^3) was used to calculate impacts.

Table 3-50. Top 99% of the LCD aesthetic (odor) impacts score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LCD monitor/module mfg.	Phosphine	Primary	89%
Manufacturing	LPG production	Hydrogen sulfide	Secondary	6.8%
Use	U.S. electric grid	Acetaldehyde	Model/secondary	1.4%
Manufacturing	LCD monitor/module mfg.	Ammonia	Primary	1.2%
Manufacturing	LCD monitor/module mfg.	Acetic acid	Primary	0.44%

*Column may not add to 99% due to rounding.

Other significant contributors include hydrogen sulfide from LPG production, acetaldehyde from the U.S. electric grid, and ammonia and acetic acid from LCD module/monitor manufacturing. Most of the LPG made in the LPG production process is used as a fuel in LCD glass manufacturing, indicating this process is ultimately responsible for LPG production impacts. However, LCD glass energy inputs are uncertain and evaluated in a sensitivity analysis (Section 3.4). LCD monitor/module manufacturing data were collected directly from manufacturers by the CDP, while the LPG production inventory was obtained from *Ecobilan.* The U.S. electric grid inventory was developed by CDP researchers from secondary sources.

Limitations and Uncertainties

Aesthetic (odor) impact scores are based on the identity and amount of odor-causing chemicals (Heijungs *et al.*, 1992; EPA, 1992), released to the air divided by their chemical-specific OTVs. An OTV is the lowest concentration of a substance in air that can be smelled based on a standardized test. Limitations and uncertainties in the aesthetics impact score stem from structural or model uncertainty (whether or not odor thresholds will actually be exceeded), OTV data uncertainty (how well published OTVs represent the odor threshold of different populations), and LCI data uncertainty.

The aesthetics impact score calculates the mass of malodorous air that could result if a chemical release occurs in a finite volume of air. It does not predict whether actual odor impacts will occur. This is because LCI data do not describe the time rate of release or whether dilution and mixing with ambient air will dilute the concentration of a pollutant to below its odor threshold. In addition, odor thresholds are highly variable because of the differing ability of individuals to detect odors. Therefore, the impact scores may not account for odors perceived by the most sensitive populations or may overstate impacts perceived by less sensitive populations. Finally, the aesthetic impact scores are subject to the limitations and uncertainties in the LCI data, since they are calculated from air emissions data in the inventories. The limitations and uncertainties in LCI data were discussed in Section 2.2.2.2, and have been discussed extensively with LCIA results for other impact categories, above.

3.3.14 Ecotoxicity

Ecotoxicity refers to effects of chemical outputs on non-human living organisms. As discussed in Section 3.1.2.13, ecotoxicity impact categories included in the scope of this LCA include impacts to aquatic and terrestrial organisms.

Ecotoxicity impacts are calculated using the scoring of inherent properties approach where an impact score is based on the inventory amount weighed by a hazard value (HV). The HV represents the toxicity of a specific material to aquatic or terrestrial organisms (see Table K-8 in Appendix K for a list of toxicity values used to calculate hazard values). Aquatic HVs are based on acute and chronic toxicity values for fish, while terrestrial HVs are based on chronic noncancer toxicity values for mammals, usually rodents. Similar to the chronic human health impacts discussed in Section 3.3.13, the inventory amount (the toxic chemical outputs to water for aquatic toxicity effects, and the outputs to air and water for terrestrial toxicity effects) is used as a surrogate for exposure, while the hazard value represents the inherent toxicity of the substance.

Also like the human health effects methodology, the CDP ecotoxicity LCIA methodology does not consider the fate and transport of a toxic chemical in the environment, nor does it evaluate the potential for actual exposures to occur. In addition, the methodology is limited in that it does not consider toxicity data from all types of aquatic or terrestrial species, but rather focuses on a few selected species for which more toxicity data are available. The limitations and uncertainties in the ecotoxicity scores are discussed further below, following the presentation of results.

3.3.14.1 Aquatic toxicity

Figure 3-21 presents the CRT and LCD LCIA results for the aquatic toxicity impact category, based on the impact assessment methodology presented in Section 3.1.2.13. Complete results for the CRT and LCD are presented in Tables M-37 and M-38 in Appendix M, respectively.

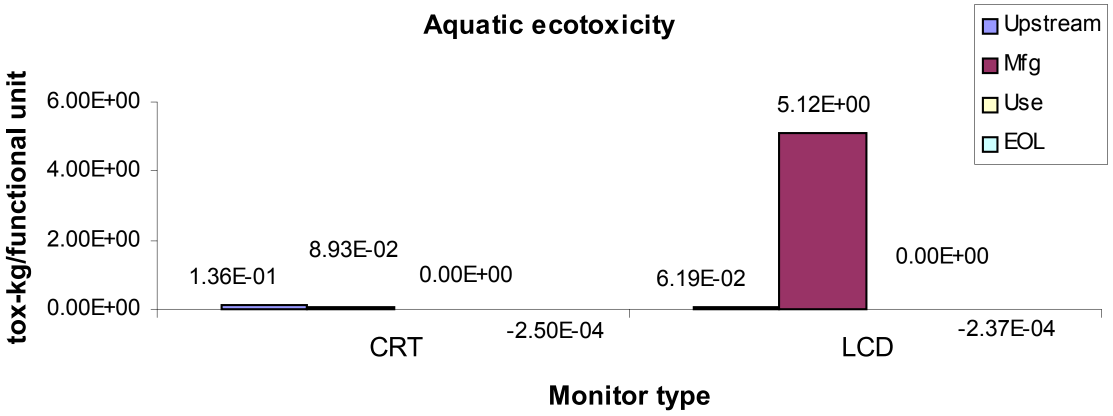

Figure 3-21. Aquatic ecotoxicity impacts by life-cycle stage

The life-cycle aquatic toxicity indicator is 0.22 tox-kg per functional unit for the CRT and 5.19 tox-kg per functional unit for the LCD. As shown in the figure, the CRT aquatic toxicity indicator is driven by water releases in the materials processing stage (64% of total), while the LCD aquatic toxicity indicator is completely dominated by water releases in the manufacturing stage (99% of total). Both monitor types receive zero scores in the use stage and small, negative values at end of life. Negative values are due to the offset of electric power plant emissions from incineration with energy recovery.

Table 3-51 lists the materials that contribute to the top 99% of the CRT aquatic toxicity impact score and the LCI data type. As shown in the table, CRT aquatic toxicity impacts are broadly distributed across a number of different process groups, with most of the top contributors responsible for less than five percent of the impacts. Most of the LCI data from which the scores were calculated are from secondary data sets, although a substantial fraction are from primary data collected to meet the goals and scope of the CDP LCA. Water releases of phosphorus from CRT tube manufacturing represents the single largest contributor to the CRT aquatic toxicity score, accounting for 26% of the total. Aquatic toxicity impacts for phosphorus are driven more by its inherent acute toxicity than the output amount. The phosphorus acute HV is calculated from a fish LC_{50} of 0.020 mg/L, which is significantly more toxic than the geometric mean value of 23.5 mg/L.

The only other specific outputs that contribute more than five percent of the CRT aquatic toxicity score are water discharges of aluminum ions (valence = +3) and copper ions (valence = +1 and +2) from aluminum production. The aluminum HV is calculated from an LC_{50} value of 36 mg/L and a NOAEL value of 3.6 mg/L, which are within an order of magnitude of the geometric mean values of 23.5 mg/L and 3.9 mg/L. Copper, on the other hand, is much more toxic to fish, with an LC_{50} value of 0.014mg/L and a NOAEL value of 0.004 mg/L. The aluminum aquatic toxicity score exceeds that of copper because it is discharged in much greater quantities.

Table 3-51. Top 99% of the CRT aquatic toxicity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	CRT tube manufacturing	Phosphorus (yellow or white)	Primary	26%
Materials processing	Aluminum production	Aluminum (+3)	Secondary	12%
Materials processing	Aluminum production	Copper (+1 & +2)	Secondary	9.5%
Materials processing	Invar	Copper (+1 & +2)	Secondary	5.0%
Materials processing	Invar	Aluminum (+3)	Secondary	4.4%
Materials processing	Invar	Zinc (+2)	Secondary	4.0%
Materials processing	Lead	Aluminum (+3)	Secondary	3.6%
Manufacturing	CRT tube manufacturing	Fluoride	Primary	3.1%
Materials processing	Ferrite manufacturing	Zinc (+2)	Secondary	3.0%
Materials processing	Aluminum production	Zinc (+2)	Secondary	2.9%
Materials processing	ABS production	Ammonia	Secondary	2.7%
Materials processing	Lead	Copper (+1 & +2)	Secondary	2.7%
Manufacturing	CRT glass/frit mfg.	Fluorides (F-)	Primary	2.6%
Manufacturing	CRT tube manufacturing	Zinc (elemental)	Primary	2.3%
Manufacturing	CRT tube manufacturing	Copper	Primary	2.1%
Materials processing	Steel production, cold-rolled, semi-finished	Phosphorus (yellow or white)	Secondary	2.0%
Manufacturing	LPG production	Phenol	Secondary	1.9%
Materials processing	Steel production, cold-rolled, semi-finished	Ammonia	Secondary	1.2%
Manufacturing	LPG production	Aluminum (+3)	Secondary	1.1%
Materials processing	Lead	Zinc (+2)	Secondary	0.82%
Materials processing	Polycarbonate production	Copper (+1 & +2)	Secondary	0.54%
Materials processing	Steel production, cold-rolled, semi-finished	Copper (+1 & +2)	Secondary	0.45%
Materials processing	Ferrite manufacturing	Aluminum (+3)	Secondary	0.43%
Materials processing	Aluminum production	Barium sulfate	Secondary	0.40%
Materials processing	ABS production	Aluminum (+3)	Secondary	0.39%
Materials processing	Invar	Ammonia	Secondary	0.36%
Materials processing	Ferrite manufacturing	Copper (+1 & +2)	Secondary	0.31%
Materials processing	ABS production	Copper (+1 & +2)	Secondary	0.25%
Materials processing	Styrene-butadiene copolymer production	Copper (+1 & +2)	Secondary	0.24%
Materials processing	Aluminum production	Titanium tetrachloride	Secondary	0.20%
Materials processing	Polycarbonate production	Mercury compounds	Secondary	0.19%
Materials processing	Aluminum production	Strontium (Sr II)	Secondary	0.14%

Table 3-51. Top 99% of the CRT aquatic toxicity impact score

Life-cycle stage	**Process group**	**Material**	**LCI data type**	**Contribution to impact score***
Materials processing	Steel production, cold-rolled, semi-finished	Aluminum (+3)	Secondary	0.12%
Materials processing	Ferrite manufacturing	Ammonia	Secondary	0.12%
Materials processing	Lead	Barium sulfate	Secondary	0.10%
Materials processing	Steel production, cold-rolled, semi-finished	Nitrogen dixode	Secondary	0.088%
Materials processing	ABS production	Mercury compounds	Secondary	0.088%
Materials processing	Steel production, cold-rolled, semi-finished	Zinc (+2)	Secondary	0.087%
Materials processing	Styrene-butadiene copolymer production	Mercury compounds	Secondary	0.086%
Materials processing	Steel production, cold-rolled, semi-finished	Fluorides (F-)	Secondary	0.086%
Materials processing	Aluminum production	Lead compounds	Secondary	0.076%
Materials processing	Polycarbonate production	Zinc (+2)	Secondary	0.076%
Materials processing	Invar	Strontium (Sr II)	Secondary	0.074%

*Column may not add to 99% due to rounding.

Table 3-52 lists the materials that contribute to the top 99% of the LCD aquatic toxicity impact score and the LCI data type. Unlike the CRT, LCD impacts in this category are not distributed across a number of different process groups, but dominated by phosphorus emissions from a single process group, LCD monitor/module manufacturing. Phosphorus releases from LCD monitor/module manufacturing are several orders of magnitude higher than phosphorus releases from CRT tube manufacturing (the greatest contributor to the CRT aquatic toxicity impact score). However, the LCD aquatic toxicity score for phosphorus is still driven by the inherent acute toxicity of phosphorus, rather than the release amount.

Other top contributors to LCD impacts in this category include ammonia releases from PMMA sheet production, and phosphorus emissions from LCD panel components manufacturing. No toxicity data were available for ammonia. Consequently, it was assigned a default HV of two, representative of mean acute and chronic fish toxicity values.

Table 3-52. Top 99% of the LCD aquatic toxicity impact score

Life-cycle stage	**Process group**	**Material**	**LCI data type**	**Contribution to impact score**
Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	Primary	98%
Materials processing	PMMA sheet production	Ammonia	Secondary	0.63%
Manufacturing	LCD panel components	Phosphorus (yellow or white)	Primary	0.56%

3.3.14.2 Terrestrial ecotoxicity

Figure 3-22 presents the CRT and LCD LCIA results for the terrestrial toxicity impact category, based on the impact assessment methodology presented in Section 3.1.2.13. Complete results for the CRT and LCD are presented in Tables M-39 and M-40 in Appendix M, respectively.

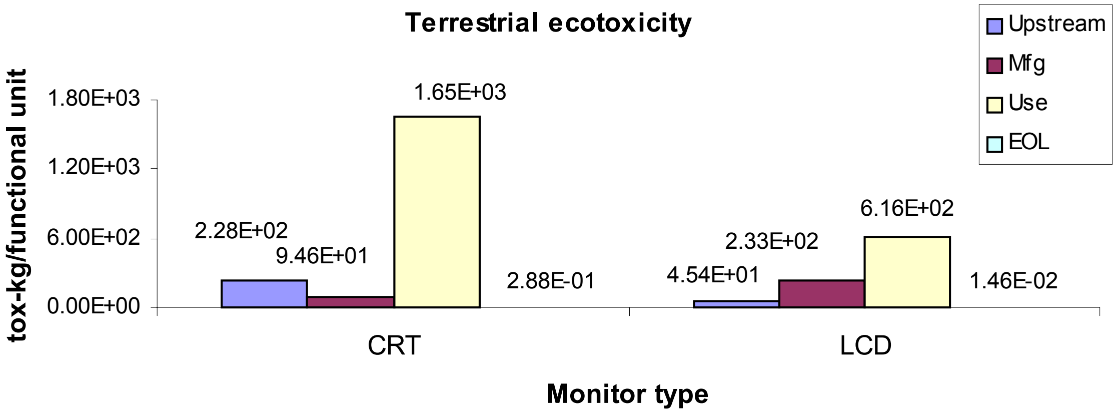

Figure 3-22. Terrestrial ecotoxicity impacts by life-cycle stage

The life-cycle terrestrial toxicity indicator is 1,970 tox-kg per functional unit for the CRT and 894 tox-kg per functional unit for the LCD. As shown in the figure, the CRT result is dominated by toxic chemical outputs from electricity generation in the use stage, which account for almost 84% of CRT impacts in this category. To a lesser degree, LCD terrestrial toxicity impacts are also driven by emissions from electricity generation in the use stage, which account for more than 69% of the total.

The materials processing stage contributes about 12% of CRT terrestrial toxicity impacts and about five percent of LCD impacts. The manufacturing life-cycle stage is responsible for five and 26% of CRT and LCD impacts in this category, respectively. Both monitors receive very small terrestrial toxicity scores at end of life. This is because most terrestrial toxicity impacts from CRT and LCD recycling and disposal processes are offset by a credit on electric grid emissions when the monitors are incinerated with energy recovery.

The terrestrial toxicity impact results are almost identical to the chronic public health effects results presented previously (see Section 3.3.13). Recall that human health and terrestrial toxicity impacts are calculated using the same noncancer toxicity values (and the same inventory data), with the main difference being that toxicity data on carcinogenic effects are excluded from the terrestrial toxicity impact calculations. However, human health and terrestrial toxicity impacts are almost identical because: (1) impacts in both categories are dominated by emissions of sulfur dioxide from electricity generation (see Tables 3-53 and 3-54 below for top contributors to the CRT and LCD terrestrial toxicity impacts), and (2) sulfur dioxide has a high hazard value for noncancer effects and a hazard value of zero for cancer effects.

Table 3-53 presents the materials that contribute to the top 99% of the CRT terrestrial toxicity impact score. As already noted, SO_2 emissions from a number of different process groups almost completely dominate CRT impacts in this category, accounting for slightly less than 99% of the total. Most of these emissions are from the combustion of fossil fuels to generate electricity. All of the SO_2 LCI data are either from secondary data sets not developed specifically for the CDP or from the electric grid inventories developed from secondary sources for this project. Sulfur dioxide has a relatively high HV, based on an inhalation NOAEL of 0.104 mg/m^3 and the geometric mean inhalation NOAEL of 68.7 mg/m^3. In addition, as noted in the section on human health effects (3.3.13), from a mass loading perspective (i.e., based on the inventory alone), SO_2 emissions were the second largest contributor to CRT life-cycle air pollutant emissions, exceeded only by emissions of carbon dioxide (CO_2). Carbon dioxide is not classified as toxic, and therefore did not contribute to the terrestrial toxicity impact category.

Table 3-53. Top 99% of the CRT terrestrial toxicity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	83%
Materials processing	Invar	Sulfur dioxide	Secondary	8.4%
Manufacturing	Japanese electric grid	Sulfur dioxide	Model/secondary	2.9%
Manufacturing	U.S. electric grid	Sulfur dioxide	Model/secondary	1.3%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur dioxide	Secondary	1.3%
Materials processing	Aluminum production	Sulfur dioxide	Secondary	0.70%
Materials processing	Polycarbonate production	Sulfur dioxide	Secondary	0.40%
Manufacturing	LPG production	Carbon monoxide	Secondary	0.27%

* Column may not add to 99% due to rounding.

Table 3-54 lists the materials that contribute to the top 99% of the LCD terrestrial toxicity impact score and the LCI data type. LCD impacts in this category are also dominated by SO_2 emissions, which are responsible for roughly 92% of impacts. Like the CRT, most of these emissions occur from electricity generation, either during the use stage (68%) or manufacturing (21%). As noted previously, SO_2 has a relatively high HV, due to its low toxicity value (inhalation NOAEL = 0.104 mg/m^3). Similar to the CRT, from a mass loading perspective (i.e., based on the inventory alone), SO_2 emissions were the second largest contributor to LCD life-cycle air pollutant emissions, exceeded only by emissions of CO_2.

Other top contributors to the LCD terrestrial toxicity score include phosphine and phosphorus from LCD monitor/module manufacturing, and carbon monoxide and methane from natural gas production. As noted above in the section on chronic occupational health effects, the phosphine, phosphorus, and benzene scores are driven more by their inherent toxicity than their output amounts.

Table 3-54. Top 99% of the LCD terrestrial toxicity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	68%
Manufacturing	Japanese electric grid	Sulfur dioxide	Model/secondary	21%
Manufacturing	LCD monitor/module mfg.	Phosphine	Primary	3.2%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur dioxide	Secondary	1.4%
Materials processing	PMMA sheet production	Sulfur dioxide	Secondary	0.96%
Materials processing	Natural gas production	Benzene	Secondary	0.59%
Materials processing	Aluminum production	Sulfur dioxide	Secondary	0.57%
Materials processing	Natural gas production	Carbon monoxide	Secondary	0.50%
Materials processing	Polycarbonate production	Sulfur dioxide	Secondary	0.50%
Materials processing	Natural gas production	Methane	Secondary	0.39%
Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	Primary	0.38%

3.3.14.3 Terrestrial toxicity impact scores modified to exclude sulfur dioxide

Because the terrestrial toxicity impact scores for both the CRT and the LCD are dominated by SO_2 emissions, a secondary analysis was run to identify the top contributors to these impacts when SO_2 emissions are excluded from the inventories. Results of this analysis may be more useful to manufacturers seeking to identify problematic toxic chemicals within their own manufacturing processes.

Figure 3-23 presents the CRT and LCD terrestrial toxicity impact scores by life-cycle stage when SO_2 emissions are excluded from the inventories. Under this scenario, the CRT score is reduced almost 99% from 1,970 tox-kg to 21 tox-kg per functional unit, and the LCD score is reduced about 94%, from 894 tox-kg to 54 tox-kg per functional unit. Note that these scores should not be used to evaluate which monitor type has higher overall impacts in this category, but they are useful for identifying life-cycle improvement opportunities that were previously obscured by SO_2 impacts.

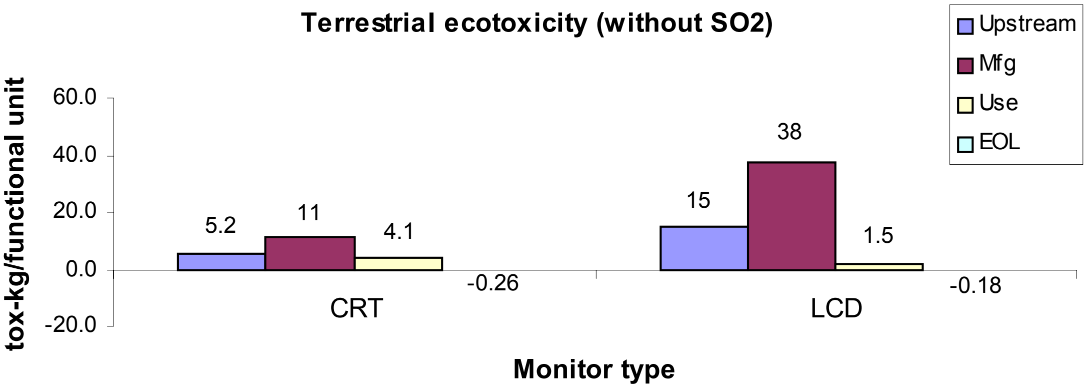

Figure 3-23. Terrestrial ecotoxicity impacts (without SO2) by life-cycle stage

With SO_2 emissions removed from the inventories, terrestrial toxicity impacts are highest in the manufacturing life-cycle stage for both the CRT (56% of impacts) and the LCD (70% of impacts). The materials processing stage is the next largest contributor for both monitor types, contributing 25% of CRT impacts and 27% of LCD impacts, followed by the use stage, which contributes 20% of CRT impacts and almost 3% of LCD impacts. Both monitors have slight negative values at end-of-life, due to the offset of electric grid emissions from incineration with energy recovery.

Table 3-55 presents the materials that contribute greater than one percent of CRT terrestrial toxicity impacts when SO_2 emissions are excluded from the CRT inventory. Like the modified public chronic human health effects results discussed in Section 3.3.13, under this scenario CRT chronic public health impacts are still being driven by emissions of criteria air pollutants, including carbon monoxide, nitrogen oxides, and sulfur oxides (assuming that SO_2 emissions comprise a large part of the sulfur oxide emissions shown in the table). As shown in the table, emissions of these three pollutants or pollutant categories are responsible for some 46% of CRT terrestrial toxicity impacts when pure SO_2 emissions are excluded from the CRT inventory. Note that the majority of these emissions occur from the LPG production process, and most of this LPG is used as a fuel in CRT glass manufacturing. CRT glass manufacturing energy inputs are uncertain and evaluated in a sensitivity analysis (see Section 3.4). Other significant contributors include arsenic from lead production, methane from LPG production and the U.S. electric grid inventory, vanadium and benzene from LPG production, and titanium tetrachloride from aluminum production.

Table 3-55. Materials contributing greater than 1% of the CRT terrestrial toxicity impact score (without SO_2)

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LPG production	Carbon monoxide	Secondary	26%
Materials processing	Lead	Arsenic	Secondary	11%
Use	U.S. electric grid	Nitrogen oxides	Model/secondary	5.7%
Manufacturing	LPG production	Vanadium	Secondary	5.1%
Use	U.S. electric grid	Carbon monoxide	Model/secondary	4.9%
Manufacturing	LPG Production	Benzene	Secondary	4.2%
Manufacturing	LPG production	Methane	Secondary	4.1%
Manufacturing	LPG production	Sulfur oxides	Secondary	3.9%
Materials processing	Aluminum production (all virgin)	Titanium tetrachloride	Secondary	3.5%
Use	U.S. electric grid	Methane	Model/secondary	3.1%
Manufacturing	CRT glass/frit mfg.	Fluorides (F-)	Primary	2.8%
Manufacturing	LPG production	Nitrogen oxides	Secondary	2.8%
Use	U.S. electric grid	Arsenic	Model/secondary	2.7%
Use	U.S. electric grid	Hydrochloric acid	Model/secondary	2.4%
Materials processing	Steel Prod., cold-rolled, semi-finished	Carbon monoxide	Secondary	1.4%
Materials processing	Invar	Titanium tetrachloride	Secondary	1.2%
Manufacturing	CRT tube manufacturing	Carbon monoxide	Primary	1.0%
Materials processing	Lead	Titanium tetrachloride	Secondary	1.0%
Manufacturing	LPG production	Arsenic	Secondary	1.0%

Table 3-56 presents the materials that contribute greater than one percent of LCD terrestrial toxicity impacts when SO_2 emissions are excluded from the LCD inventory. As with the LCD modified chronic human health results discussed in Section 3.3.13, when SO_2 emissions are excluded, phosphine emissions from LCD monitor/module manufacturing are the dominant factor in the LCD terrestrial toxicity score, contributing 53% of the total. Other significant contributors include benzene, carbon monoxide, methane, and nitrogen oxides from natural gas production, and phosphorus, fluorides, tetramethyl ammonium hydroxide, and nitrogen oxides from LCD monitor/module manufacturing. Recall that the LCD monitor/module manufacturing process consumes the majority of the natural gas made in the natural gas production process, where LNG is used as an ancillary material. However, only one of the seven LCD monitor/module manufacturers that provided inventory data to the CDP reported the ancillary use of LNG. Other manufacturers reported using LNG as a fuel.

Table 3-56. Materials contributing greater than 1% of the LCD terrestrial toxicity impact score (without SO_2)

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LCD module/monitor mfg.	Phosphine	Primary	53%
Materials processing	Natural gas production	Benzene	Secondary	9.8%
Materials processing	Natural gas production	Carbon monoxide	Secondary	8.2%
Materials processing	Natural gas production	Methane	Secondary	6.5%
Manufacturing	LCD module/monitor mfg.	Phosphorus (yellow or white)	Primary	6.3%
Manufacturing	LCD module/monitor mfg.	Fluorides (F-)	Primary	4.7%
Materials processing	Natural gas production	Nitrogen oxides	Secondary	1.2%
Manufacturing	LCD module/monitor mfg.	Tetramethyl ammonium hydroxide	Primary	1.2%
Manufacturing	LCD module/monitor mfg.	Nitrogen oxides	Primary	1.0%

3.3.14.4 Limitations and uncertainties

Most of the limitations and uncertainties in the ecotoxicity results are similar to the limitations and uncertainties in the human health effects scores. The reader is referred to Section 3.3.13 for a full discussion of these limitation and uncertainties. In summary, they can be grouped into three categories:

1. *Structural or modeling limitations and uncertainties* associated with the accuracy of the toxic chemical classification method and the chemical scoring approach used to characterize human health effects.
2. *Toxicity data limitations and uncertainties* associated with the availability and accuracy of toxicity data to represent ecotoxicity.
3. *LCI data limitations and uncertainties* associated with the accuracy and representativeness of the inventory data.

With regard to toxicity data, other limitations and uncertainties in the ecotoxicity results are related to the use of surrogates to assess toxicity to all species within an impact category. For example, the aquatic toxicity category uses fish (usually the fathead minnow) as a surrogate to assess toxicity to all aquatic organisms, but it has been well-established in the ecotoxicology literature that fish are not the most sensitive test species to all or most industrial chemicals. In fact, invertebrates (daphnids) or algae (Selenastrum) often are more sensitive to particular chemicals than fish (Smrchek, 1999). Similarly, the terrestrial toxicity category uses mammals, primarily rodents, as a surrogate to assess toxicity to all terrestrial organisms. Terrestrial plants and soil organisms (insects, earthworms, etc.) are not considered, but both of these may be more sensitive than mammals.

Because there are difficulties in comparing test endpoints for different types of organisms, and because there is a very limited toxicity database for some of the other organisms, the LCIA methodology employed in this study uses fish as a surrogate for aquatic toxicity and mammals as a surrogate for terrestrial ecotoxicity. This helps to reduce data gaps and the difficulties in comparing test endpoints for different types of organisms. Furthermore, we believe this approach to be acceptable for a study, such as the CDP LCA, that gives relative ranking of impacts from different chemicals or process groups instead of absolute values. However, it should be noted that this approach can result in an underestimation of the absolute ecotoxicity and hazards of chemicals.

With regard to LCI data limitations not discussed previously, it should be noted that the CRT and LCD LCAs do not address spills or other accidental releases that could have significant adverse effects on aquatic or terrestrial organisms. This is a common limitation of LCA, which is often too labor-intensive to address different operational scenarios across the product life cycle.

3.3.15 Summary of Top Contributors by Impact Category

Tables 3-57 and 3-58 summarize the top contributors to CRT and LCD life-cycle impacts by impact category. As shown in Table 3-57, CRT impacts are largely driven by two factors: (1) the large amount of LPG fuel used in CRT glass/frit manufacturing, and (2) the relatively large amount of electricity consumed during the use stage. The LPG production process yields the CRT's top contributor in eight of 20 impact categories. Most of this LPG is used as a fuel source in CRT glass manufacturing in the glass/frit process group, which, in turn, produces the top contributor to two of 20 impact categories. Thus, LPG used in the glass/frit process group (primarily CRT glass manufacturing) is ultimately the key driver for CRT impacts in ten categories. Similarly, outputs from electricity generation during the use stage result in the top contributor to seven CRT impact categories. Note that in 14 of the 20 impact categories, the top contributor to CRT impacts is responsible for more than 50% of impacts.

Both the glass manufacturing energy and the use stage lifespan (which determines the amount of electricity generated during the use stage) are evaluated in a sensitivity analysis in Section 3.4. In the modified glass energy sensitivity analysis, LPG inputs are greatly reduced and impacts are therefore reduced, but in the modified lifespan (manufactured life) sensitivity analysis, the number of hours a monitor is in use is increased. Thus, CRT impacts are increased.

LCD impacts are not as dominated by a few data points, but a few processes (LCD monitor/module manufacturing and electricity generation in the use stage) are responsible for a large percent of the impacts. As shown in Table 3-58, both of these processes result in the top contributors to six LCD impact categories each. In addition, the process to produce LNG used as an ancillary material in LCD monitor/module manufacturing is the top contributor to an additional impact category (photochemical smog). Note that in 11 of the 20 impact categories, the top contributor to LCD impacts is responsible for more than 50% of impacts.

Like the CRT, both the glass energy inputs and use stage lifespan of the LCD are evaluated in a sensitivity analysis in Section 3.4. LCD monitor/module manufacturing energy and LCD EOL dispositions are also evaluated. LCD monitor/module manufacturing energy was selected for a sensitivity analysis because of the high degree of variability seen in data provided by manufacturers. The impacts presented in the baseline scenario are calculated with energy outliers removed from the average, but the outliers are included in the sensitivity analysis. This results in higher electricity consumption but lower fuel consumption, which, in turn, causes reduced impacts in some categories and increased impacts in others. Note that the LNG used as an ancillary material in LCD monitor/module manufacturing is not affected by the sensitivity analysis since it only focuses on materials used as an energy source.

Table 3-57. Summary of top contributors to CRT impacts by impact category

Impact category	Top contributors			
	Life-cycle stage	Process group	Material	Contribution to impact score
Renewable resource use	Manufacturing	LPG production	water	79%
Nonrenewable resource use	Manufacturing	LPG production	Petroleum (in ground)	56%
Energy use	Manufacturing	CRT glass/frit mfg.	Liquefied petroleum gas	72%
Solid waste landfill use	Use	U.S. electric grid	Coal waste	38%
Hazardous waste landfill use	End-of-life	CRT landfilling	EOL CRT monitor, landfilled	91%
Radioactive waste landfill use	Use	U.S. electric grid	Low-level radioactive waste	61%
Global warming	Use	U.S. electric grid	Carbon dioxide	64%
Ozone depletion	Use	U.S. electric grid	Bromomethane	49%
Photochemical smog	Manufacturing	LPG production	Hydrocarbons, unspeciated	36%
Acidification	Use	U.S. electric grid	Sulfur dioxide	47%
Air particulates	Manufacturing	LPG production	PM	43%
Water eutrophication	Manufacturing	LPG production	COD	72%
Water quality, BOD	Manufacturing	LPG production	BOD	96%
Water quality, TSS	Manufacturing	LPG production	Suspended solids	97%
Radioactivity	Materials Processing	Steel production, cold-rolled, semi-finished	Plutonium-241 (isotope)	62%
Chronic health effects, occupational	Manufacturing	CRT glass/frit manufacturing	Liquefied petroleum gas	78%
Chronic health effects, public	Use	U.S. electric grid	Sulfur dioxide	83%
Aesthetics (odor)	Manufacturing	LPG production	Hydrogen sulfide	94%
Aquatic toxicity	Manufacturing	CRT tube manufacturing	Phosphorus (yellow or white)	26%
Terrestrial toxicity	Use	U.S. electric grid	Sulfur dioxide	83%

Table 3-58. Summary of top contributors to LCD impacts by impact category

Impact category	Top contributors			
	Life-cycle stage	**Process group**	**Material**	**Contribution to impact score**
Renewable resource use	Manufacturing	LCD monitor/module mfg.	Water	38%
Nonrenewable resource use	Materials processing	Natural gas production	Natural gas (in ground)	65%
Energy use	Use	LCD monitor use	Electricity	30%
Solid waste landfill use	Use	U.S. electric grid	Coal waste	44%
Hazardous waste landfill use	End-of-life	LCD landfilling	EOL LCD monitor, landfilled	97%
Radioactive waste landfill use	Use	U.S. electric grid	Low-level radioactive waste	44%
Global warming	Manufacturing	LCD monitor/module mfg.	Sulfur hexafluoride	29%
Ozone depletion	Manufacturing	LCD panel components manufacturing	HCFC-225cb	34%
Photochemical smog	Materials processing	Natural gas production	Nonmethane hydrocarbons, unspeciated	45%
Acidification	Use	U.S. electric grid	Sulfur dioxide	31%
Air particulates	Materials processing	Steel production, cold-rolled, semi-finished	PM	45%
Water eutrophication	Manufacturing	LCD monitor/module mfg.	Nitrogen	67%
Water quality, BOD	Manufacturing	LCD monitor/module mfg.	BOD	61%
Water quality, TSS	Manufacturing	LPG production	Suspended solids	66%
Radioactivity	Materials processing	Steel production, cold-rolled, semi-finished	Plutonium-241 (isotope)	96%
Chronic health effects, occupational	Manufacturing	LCD monitor/module mfg.	Liquefied natural gas	58%
Chronic health effects, public	Use	U.S. electric grid	Sulfur dioxide	68%
Aesthetics (odor)	Manufacturing	LPG production	Hydrogen sulfide	94%
Aquatic toxicity	Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	98%
Terrestrial toxicity	Use	U.S. electric grid	Sulfur dioxide	68%

3.4 SENSITIVITY ANALYSES

Due to assumptions and uncertainties in this LCA, as in any LCA, several sensitivity analyses of the baseline results were conducted. Section 2.7.3 described how areas for sensitivity analyses (scenarios) were selected, and the modifications made to the baseline inventory. Sections 3.4.1 through 3.4.4 recap these modifications and present sensitivity analysis results. Section 3.4.5 summarizes the effects of different scenarios on CRT and LCD impacts.

3.4.1 Manufactured Life Scenario

Due to the uncertainty and assumptions associated with the baseline use stage lifespan (effective life) scenario, a "manufactured life" scenario was also considered. Recall that the manufactured life is defined as the length of time a monitor is designed to operate effectively, while the effective life is defined as the actual amount of time a monitor is used, by one or multiple users, before it reaches its final disposition. The manufactured life is the number of hours a monitor would function as manufactured, and is independent of user choices or actions. Section 2.4.1.3 presented a detailed discussion of how the manufactured life was determined, and is summarized below.

The manufactured life of both monitor types was estimated using the mean-time-before-failure (MTBF) specifications of the monitor and its components. From review of MTBF information obtained on CRT-based monitors (see Appendix H, Attachment A, Table A2), it appears that the CRT tube itself is the component that 99% of the time determines whether the entire monitor has reached its end-of-life. Thus, an average of the two ranges obtained on the estimated lifetime of CRT tubes (10,000 and 15,000 hours) was used as the CRT manufactured lifetime (12,500 hours).

For active matrix LCDs, the components that have the greatest potential to fail first are the display panel itself (including the liquid crystals and thin-film transistors), backlights, driver integrated circuit (IC) tabs, and other smaller components. The backlights and driver IC tabs can be field-replaced, thus their failure does not necessarily represent the end of the monitor's life. However, failure of the liquid crystals or transistors, which would require replacement of the display panel itself, would most likely mean that the monitor cannot be cost-effectively repaired. Thus, in this study, the amount of time an LCD monitor would operate during its manufactured life is assumed to be the average of the non field-replaceable values, or 45,000 hours. In order for a monitor to operate for 45,000 hours, any major field-replaceable parts that have MTBFs less than 45,000 hours are accounted for in the inventory. For example, assuming the backlights last on average 32,500 hours (the average of the values obtained for backlights), approximately 1.4 backlights on average would be needed for every panel during its 45,000 hour lifetime.

To calculate the manufactured life electricity consumption (kWh/life), the energy use rate (kW) was multiplied by the lifespan (hours/life) for each monitor in each power mode (see Table 2-20 in Section 2.4.1.3). The LCD manufactured life (45,000 hours) is 3.6 times greater than the CRT manufactured life (12,500 hours). In an LCA, comparisons are made based on functional equivalency. Therefore, if one monitor will operate for a longer period of time than another, impacts should be based on an equivalent use. Thus, based on equivalent use periods, 3.6 CRTs would need to be manufactured for every LCD. This was incorporated into the profile analysis for the manufactured life LCA. To apply the manufactured life scenario to the CRT and LCD

life-cycle profiles, the following modifications were made to the baseline (effective life) scenario:

- change the CRT electricity input in the use stage from 635 kWh (2,286 MJ) to 788 kWh (2,837 MJ); [3]
- change the LCD electricity input in the use stage from 237 kWh (853 MJ) to 1,035 kWh (3,726 MJ);
- increase the manufacturing of CRTs by a factor of 3.6 to account for the functional equivalency of CRTs and LCDs. This was done by increasing the functional unit by a factor of 3.6, which equates to manufacturing, using, and recycling or disposing of 3.6 times more CRTs than in the baseline case; and
- increase the manufacturing of the LCD backlight lamp by a factor of 1.4 to account for the functional equivalency of LCDs and CRTs. This was done by increasing the backlight lamp mass (0.0023 kg) by a factor of 1.4, which in turn results in an increase in inputs and outputs associated with manufacturing the backlilght.

Table 3-59 presents the CRT and LCD life-cycle results by impact category for the baseline and manufactured life scenarios. It also presents the percent change from the baseline to the manufactured life scenario for both monitor types. Note that the manufactured life results are most useful for evaluating the CRT and LCD together, not for comparing the CRT or LCD baseline (effective life) results to its manufactured life results. This is because the CRT and LCD manufactured life results are functionally equivalent, but the CRT to CRT and LCD to LCD effective life and manufactured life scenarios are not. The baseline for both monitor types represents impacts from manufacture and final disposition of one monitor. The CRT manufactured life scenario represents impacts from 3.6 CRT monitors and the LCD manufactured life scenario represents impacts from one LCD monitor and 1.4 backlights. However, the percent change figures are presented to better understand how the manufactured life scenario affects overall results.

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[3] This represents the electricity use for a 12,500 hour life span. This figure is then multiplied by a factor of 3.6 in the functional equivalency calculations (see third bullet, below).

Table 3-59. Baseline and sensitivity analysis results—manufactured life

		CRT			LCD		
Impact category	**Units/ Monitor**	**Baseline**	**Manu-factured**	**% change**	**Baseline**	**Manu-factured**	**% change**
Renewable resource use	kg	1.31e+04	4.83e+04	268%	2.80e+03	4.30e+03	53.5%
Nonrenewable resource use	kg	6.68e+02	2.58e+03	286%	3.64e+02	6.12e+02	68.0%
Energy use	MJ	2.08e+04	7.70e+04	270%	2.84e+03	5.71e+03	101%
Solid waste landfill use	m3	1.67e-01	6.86e-01	312%	5.43e-02	1.79e-01	230%
Hazardous waste landfill use	m3	1.68e-02	6.05e-02	260%	3.60e-03	3.60e-03	0.00%
Radioactive waste landfill use	m3	2.00e-04	8.00e-04	328%	1.00e-04	3.00e-04	194%
Global warming	kg-CO2 eq.s	6.95e+02	2.90e+03	317%	5.93e+02	1.17e+03	97.3%
Ozone depletion	kg-CFC-11 eq.s	2.05e-05	8.27e-05	304%	1.37e-05	2.66e-05	94.1%
Photochemical smog	kg-ethene eq.s	1.71e-01	6.20e-01	262%	1.41e-01	1.47e-01	4.22%
Acidification	kg-SO2 eq.s	5.25e+00	2.19e+01	317%	2.96e+00	7.29e+00	146%
Air particulates	kg	3.01e-01	1.13e+00	277%	1.15e-01	1.87e-01	63.4%
Water eutrophication	kg-phosphate eq.s	4.82e-02	**1.74e-01**[a]	260%	4.96e-02	4.96e-02	0.02%
BOD	kg	1.95e-01	7.02e-01	260%	2.83e-02	2.83e-02	0.02%
TSS	kg	8.75e-01	3.15e+00	260%	6.15e-02	6.15e-02	0.02%
Radioactivity	Bq	3.85e+07	1.14e+08	197%	1.22e+07	1.28e+07	4.49%
Chronic health effects, occupational	tox-kg	9.34e+02	3.39e+03	263%	6.96e+02	7.41e+02	6.47%
Chronic health effects, public	tox-kg	1.98e+03	8.56e+03	333%	9.02e+02	2.98e+03	230%
Aesthetics (odor)	m3	7.58e+06	2.74e+07	262%	5.04e+06	5.30e+06	5.00%
Aquatic toxicity	tox-kg	2.25e-01	8.10e-01	260%	5.19e+00	5.19e+00	0.02%
Terrestrial toxicity	tox-kg	1.97e+03	8.54e+03	333%	8.94e+02	2.97e+03	232%

[a] Bold indicates impact category indicator that reversed direction from the baseline scenario such that the CRT indicator is now greater than the LCD.

As shown in Table 3-59, under the manufactured life scenario CRT impacts exceed those of the LCD in every impact category except aquatic toxicity. CRT impacts were expected to be greater than those of the LCD in most impact categories for the following reasons:

- Under the baseline scenario CRT impacts exceeded those of the LCD in every category but water eutrophication and aquatic toxicity.
- The manufactured life scenario assumes more CRTs are manufactured than LCDs during the manufactured life lifespan, which results in greater impacts.
- The manufactured life use stage is longer than the baseline, effective life use stage, and the CRT consumes more electricity during use than the LCD.

By looking at the percent change in impact scores from the baseline to manufactured life for a monitor type we can better understand which aspect of the life-cycle is driving impacts. For example, CRT impacts increased by roughly 260% in several impact categories, which is the increase from manufacturing or disposing of an additional 2.6 monitors. Energy impacts increased by more than 260% due to the additional increase in electricity consumption during use. The CRT chronic public human health effects category increased by some 330%. This is explained by the increase in SO_2 emissions in the use stage and the high HV for SO_2, which has a proportionately greater effect on overall impacts than increased outputs of other pollutants with lower HVs in other life-cycle stages.

LCD impacts increased only slightly from the baseline to the manufactured life scenario in some impact categories, but increased up to 230% in others. Most of the LCD impact categories with less than one percent increase are for impacts related to water discharges (e.g., water eutrophication, aquatic toxicity, etc.). This is because the most significant change to the LCD inventory from the baseline to the manufactured life scenario was in the use stage, and few water discharges are reported in the U.S. electric grid inventory. On the other hand, the chronic public health effects and terrestrial toxicity impact categories show the greatest increase. These results are driven by air emissions of SO_2 from U.S. power production, which increased significantly with the longer lifespan.

To further illustrate how the longer lifespan (and additional manufacturing requirements, mainly for the CRT) in the manufactured life scenario is affecting impacts, Figures 3-24 and 3-25 compare the energy impacts and public chronic health effects, respectively, of both monitor types under the baseline and manufactured life scenarios. As shown in Figure 3-24, CRT energy impacts are still dominated by the manufacturing stage in the manufactured life scenario. This is mainly due to the large amount of LPG used to manufacture 3.6 sets of CRT glass. On the other hand, LCD energy impacts during the use stage exceeded those in manufacturing by a factor of about 2.6 in the baseline scenario, but are ten times greater in the manufactured life scenario. This is due to the longer lifespan for a single LCD in the manufactured life scenario.

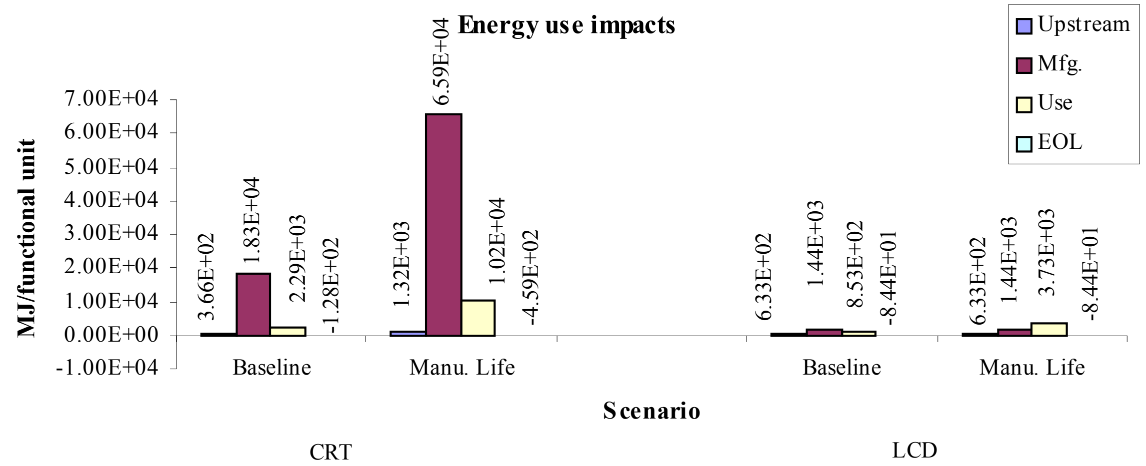

Figure 3-24. Energy use: baseline and manufactured life sensitivity results

Figure 3-25 shows that CRT chronic public health impacts are similarly distributed in the baseline and manufactured life scenarios. However, a greater percentage of LCD chronic health impacts are in the use stage under the manufactured life scenario than the baseline due to the longer use stage.

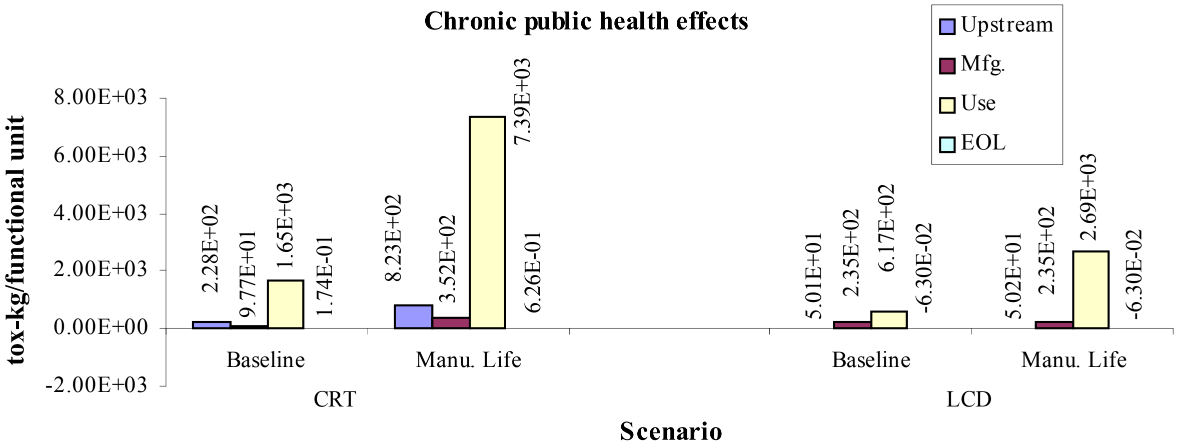

Figure 3-25. Chronic public health effects: baseline and manufactured life sensitivity results

3.4.2 Modified Glass Energy Scenario

One area of relatively large uncertainty and variability in the primary data supplied for the project was the glass manufacturing data. Both the CRT and LCD glass data were based on data supplied by CRT lead oxide (PbO) glass manufacturers, since no LCD glass manufacturers were willing to provide data to the project. To represent an LCD glass inventory, lead (Pb) materials in the CRT glass inventory were removed. Based on conversations with industry members, it was assumed that the same amount of energy per kilogram of glass produced is used to generate LCD and CRT glass. In addition, large variability among the three data sets collected resulted in a large degree of uncertainty in the glass inventory. Finally, a number of the CRT impact category results are being driven by the glass energy data or by the production process for producing the large amount of LPG used as a fuel in glass manufacturing. Consequently, the glass manufacturing inventories for both LCD and CRT glass were modified and life-cycle impacts were recalculated.

To conduct the sensitivity analysis, the energy input data for glass manufacturing were modified by removing, from the average, data that appeared unusually large, and that might be inconsistent with general industry statistics. However, industry statistics are greatly lacking when specifically considering specialty glasses such as CRT and LCD glass. Modifying the energy inputs greatly reduced the fuel energy amounts reported for the glass production process.

The baseline scenario, based on averaged primary data from manufacturers, assumed that the total energy to produce a kilogram of CRT or LCD glass was 1,560 MJ (433 kWh) of energy, with only 0.3% of that as electrical energy. The sensitivity analysis scenario assumes 16.3 MJ (4.5 kWh) per kilogram of glass produced, with approximately 30% as electrical energy. The majority of the fuel energy in the baseline scenario was from LPG. The actual input amounts are not presented here to protect the confidentiality of data provided by glass manufacturers.

Under the sensitivity (modified glass energy) scenario, only the manufacturing stage is affected, since the production of the fuels used during manufacturing is included in the manufacturing life-cycle stage. All impact categories, not only energy, are also affected because the inputs and outputs from fuel production and electricity generation processes affect each of the impact categories evaluated in this study.

Table 3-60 shows the baseline impact results and the revised impact results based on the modified glass energy inputs. The overall life-cycle impact results are highly sensitive to the energy consumption values from glass manufacturing. Under the modified glass energy scenario, the nonrenewable resource use, global warming, photochemical smog, BOD, TSS, chronic occupational health effects, and odor impact categories reversed direction such that the LCD had greater impacts within each impact category than the CRT in the overall life cycle. Note that the percent change in CRT results in most impact categories is much greater than that of the corresponding LCD results. This is because the CRT uses approximately ten times more glass than the LCD and therefore, the CRT results are much more sensitive to the glass manufacturing data than are the LCD results.

Table 3-60. Baseline and sensitivity analysis results—modified glass energy

		CRT			LCD		
Impact category	**Units/Monitor**	**Baseline**	**Glass energy**	**% change**	**Baseline**	**Glass energy[a]**	**% change**
Renewable resource use	kg	1.31e+04	2.67e+03	-79.6%	2.80e+03	2.43e+03	-13.4%
Nonrenewable resource use	kg	6.68e+02	2.35e+02	-64.8%	3.64e+02	**3.49e+02**	-4.14%
Energy use	MJ	2.08e+04	3.02e+03	-85.5%	2.84e+03	2.04e+03	-28.0%
Solid waste landfill use	m3	1.67e-01	1.23e-01	-26.0%	5.43e-02	5.27e-02	-2.82%
Hazardous waste landfill use	m3	1.68e-02	1.54e-02	-8.13%	3.60e-03	3.60e-03	-1.35%
Radioactive waste landfill use	m3	2.00e-04	2.00e-04	0.12%	1.00e-04	1.00e-04	0.01%
Global warming	kg-CO2 eq.s	6.95e+02	5.23e+02	-24.8%	5.93e+02	**5.87e+02**	-1.01%
Ozone depletion[b]	kg-CFC-11 eq.s	2.05e-05	1.97e-05	-3.75%	1.37e-05	1.37e-05	-0.18%
Photochemical smog	kg-ethene eq.s	1.71e-01	5.59e-02	-67.3%	1.41e-01	**1.37e-01**	-2.84%
Acidification	kg-SO2 eq.s	5.25e+00	4.02e+00	-23.4%	2.96e+00	2.92e+00	-1.45%
Air particulates	kg	3.01e-01	1.72e-01	-42.9%	1.15e-01	1.10e-01	-3.97%
Water eutrophication	kg-phosphate eq.s	4.82e-02	4.10e-03	-91.5%	4.96e-02	4.80e-02	-3.17%
BOD	kg	1.95e-01	7.00e-03	-96.4%	2.83e-02	**2.16e-02**	-23.8%
TSS	kg	8.75e-01	2.06e-02	-97.6%	6.15e-02	**3.09e-02**	-49.7%
Radioactivity	Bq	3.85e+07	3.16e+07	-17.9%	1.22e+07	1.22e+07	0.00%
Chronic health effects, public	tox-kg	1.98e+03	1.97e+03	-0.56%	9.02e+02	9.01e+02	-0.02%
Chronic health effects, occupational	tox-kg	9.34e+02	2.30e+02	-75.4%	6.96e+02	**6.63e+02**	-4.74%
Aesthetics (odor)	m3	7.58e+06	1.09e+04	-99.9%	5.04e+06	**4.79e+06**	-4.99%
Aquatic toxicity	tox-kg	2.25e-01	2.18e-01	-3.07%	5.19e+00	5.19e+00	0.01%
Terrestrial toxicity	tox-kg	1.97e+03	1.97e+03	-0.42%	8.94e+02	8.94e+02	-0.01%

[a] Bold indicates impact category indicator that reversed direction from the baseline scenario such that the LCD indicator is now greater than the CRT.

[b] LCD impacts in this category are greater than CRT impacts when phased out substances are removed from the inventories (see Section 3.3.6).

The energy impacts for the baseline and modified glass energy scenarios are presented in Figure 3-26. In the baseline scenario, over 18,000 MJ of energy were consumed per CRT monitor during manufacturing. Almost 83% of this was from the glass/frit process group, mainly from glass manufacturing energy alone. When the glass energy inputs are reduced under the modified scenario, total energy use in the CRT manufacturing stage decreases some 97% to just under 500 MJ, and the use stage dominates the overall life-cycle energy impacts at approximately 2,300 MJ per functional unit (i.e., per monitor). The 97% decrease in manufacturing stage energy use is due to the reduced glass manufacturing fuel inputs and the consequent reduction in energy inputs to the fuel production process.

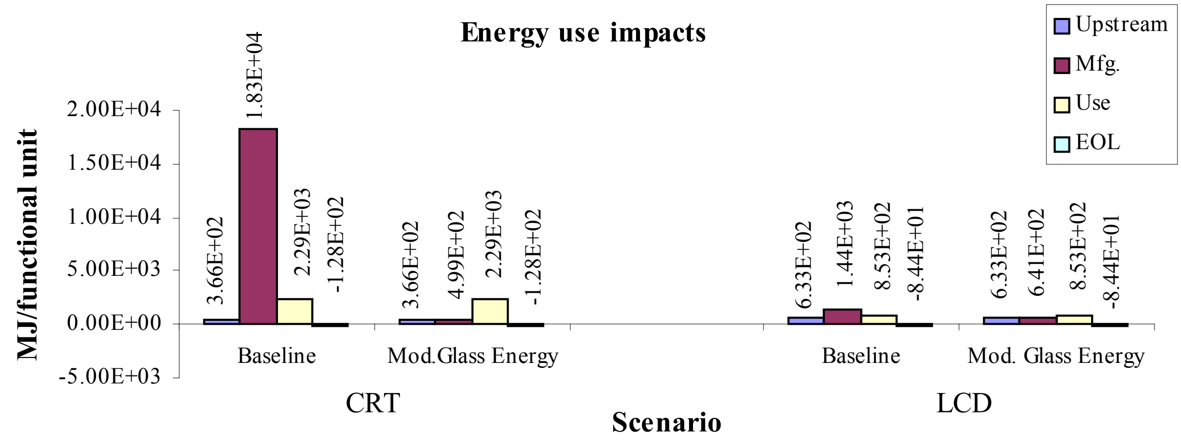

Figure 3-26. Energy impacts: baseline and modified glass energy sensitivity results

The modified glass energy scenario has a lesser, but still significant, effect on the distribution of LCD energy impacts across life-cycle stages. Under the sensitivity scenario, the LCD manufacturing stage energy consumption is reduced 55% from 1,440 MJ per monitor to about 640 MJ per monitor, and the use stage becomes the biggest energy consumer at about 850 MJ per monitor.

Global warming is one of the impact categories in which the CRT has the greater impacts than the LCD under the baseline scenario, but the LCD has the greater impacts under the sensitivity analysis. Figure 3-27 shows the global warming impacts for both monitor types under the baseline and modified glass energy scenarios. Under the latter scenario, CRT global warming impacts in the manufacturing stage are reduced some 85%, but LCD impacts are only reduced 2.5%. Again, this illustrates the greater sensitivity of CRT impact results to glass energy inputs. Also, as discussed in Section 3.3.5, a large part of LCD global warming impacts are driven by sulfur hexafluoride emissions from LCD monitor/module manufacturing, which are unaffected by the revised glass energy scenario.

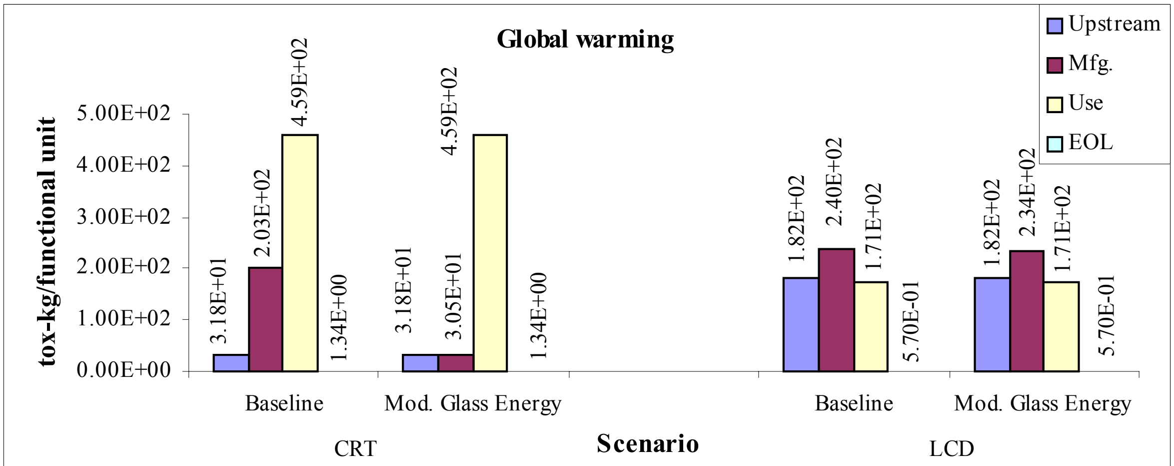

Figure 3-27. Global warming: baseline and modified glass energy sensitivity results

3.4.3 Modified LCD Module Energy Scenario

LCD monitor/module manufacturing energy was another area of relatively large uncertainty and variability in the inventory data. As discussed in Section 2.7.3.3, total energy inputs reported in six data sets received from LCD monitor/module manufacturers in Japan and Korea ranged from 330 MJ to 7,310 MJ, with a mean and standard deviation of 2,269 MJ and 2,906 MJ, respectively. The manufacturing energy data reported in two of the data sets were found to be outliers and removed from the averages used in the baseline inventory. However, for this sensitivity analysis, the outliers were added back in to the averages. Thus, to apply the modified LCD manufacturing energy scenario to the LCD profile, the following modifications were made to electricity and fuels:

- changed the electric energy inputs to the LCD monitor/module manufacturing process group from 82.1 kWh (253 MJ) per monitor to 70.1 kWh (217 MJ) per monitor,
- changed the fuel oil # 4 inputs from 0.25 kg to 0.30 kg per monitor,
- changed the kerosene inputs from 0.35 kg to 0.23 kg per monitor,
- changed the LPG inputs from 0.68 kg to 0.45 kg per monitor,
- changed the LNG inputs from 3.8 kg to 45 kg per monitor, and
- changed the natural gas inputs from 0.99 to 0.70 kg per monitor.

Note that one LCD monitor/module manufacturer also reported using a large amount of LNG as an ancillary material. However, this input amount is not affected by the sensitivity analysis, which only deals with inputs used as an energy source.

Table 3-61 presents the baseline impact results and the revised LCD impact results based on the modified LCD module energy scenario. It also shows the baseline CRT results. Under the modified LCD energy scenario, LCD impacts in ten categories actually decrease slightly, due to the slight decrease in average electrical energy consumed during LCD monitor/module manufacturing. However, impacts in six categories increase slightly, and impacts in four categories (nonrenewable resource use, energy use, photochemical smog and chronic occupational health effects) increase by more than 10%. As expected, life-cycle energy impacts are the most affected by this sensitivity analysis, due to the increased fuel consumption during manufacturing. However, under this scenario, none of the impact category results reversed direction from the baseline such that the LCD now has greater impacts than the CRT or vice versa, where the baseline LCD impacts were greater than the CRT.

Table 3-61. Baseline and sensitivity analysis results—LCD modified module energy

Impact category	Units/Monitor	CRT	LCD		
		Baseline	Baseline	Mod. energy	% change
Renewable resource use	kg	1.31e+04	2.80e+03	2.78e+03	-0.69%
Nonrenewable resource use	kg	6.68e+02	3.64e+02	4.06e+02	11.4%
Energy use	MJ	2.08e+04	2.84e+03	4.68e+03	64.9%
Solid waste landfill use	m3	1.67e-01	5.43e-02	5.47e-02	0.74%
Hazardous waste landfill use	m3	1.68e-02	3.60e-03	3.60e-03	-0.01%
Radioactive waste landfill use	m3	2.00e-04	1.00e-04	1.00e-04	-3.88%
Global warming	kg-CO2 eq.s	6.95e+02	5.93e+02	6.17e+02	4.05%
Ozone depletion[a]	kg-CFC-11 eq.s	2.05e-05	1.37e-05	1.37e-05	-0.26%
Photochemical smog	kg-ethene eq.s	1.71e-01	1.41e-01	1.61e-01	13.7%
Acidification	kg-SO2 eq.s	5.25e+00	2.96e+00	3.00e+00	1.48%
Air particulates	kg	3.01e-01	1.15e-01	1.19e-01	3.85%
Water eutrophication	kg-phosphate eq.s	4.82e-02	4.96e-02	4.96e-02	0.00%
BOD	kg	1.95e-01	2.83e-02	2.83e-02	-0.12%
TSS	kg	8.75e-01	6.15e-02	6.13e-02	-0.30%
Radioactivity	Bq	3.85e+07	1.22e+07	1.22e+07	-0.09%
Chronic health effects, occupational	tox-kg	9.34e+02	6.96e+02	7.66e+02	10.1%
Chronic health effects, public	tox-kg	1.98e+03	9.02e+02	8.82e+02	-2.14%
Aesthetics (odor)	m3	7.58e+06	5.04e+06	5.04e+06	0.01%
Aquatic toxicity	tox-kg	2.25e-01	5.19e+00	5.19e+00	0.02%
Terrestrial toxicity	tox-kg	1.97e+03	8.94e+02	8.74e+02	-2.25%

[a] LCD impacts in this category are greater than CRT impacts when phased out substances are removed from the inventories (see Section 3.3.6).

Figure 3-28 presents the LCD baseline and sensitivity analysis results for the energy use impact category, the category with the greatest percent change from the baseline to the modified LCD module energy scenario. Under this scenario, LCD energy use impacts in the manufacturing stage increased almost 230% from 1,440 MJ per functional unit to 3,280 MJ per functional unit. However, total life-cycle energy use impacts increased only 65%. This sensitivity analysis did not affect consumption rates outside of the manufacturing stage.

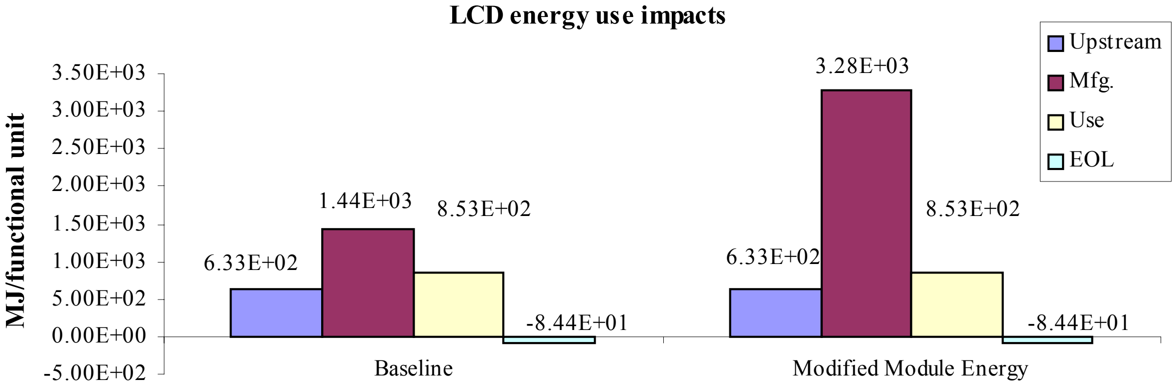

Figure 3-28. Energy use: LCD baseline and modified module energy sensitivity results

Figure 3-29 shows the effects of the sensitivity analysis on LCD chronic occupational health effects, another impact category with a relatively large percentage change. As shown in the figure, the manufacturing stage impact score in this category increased about ten percent, from 684 tox-kg per monitor to 755 tox-kg per monitor, due to the increase in fuel inputs. The chronic occupational health effect impacts were less sensitive than energy impacts because health effects results are calculated using a scoring approach that considers the inherent toxicity of a chemical instead of a simple loading approach (as is used for energy impacts). No toxicity data were available for LNG, the input with the greatest change in quantity. Therefore, the LNG HV is representative of a mean toxicity value.

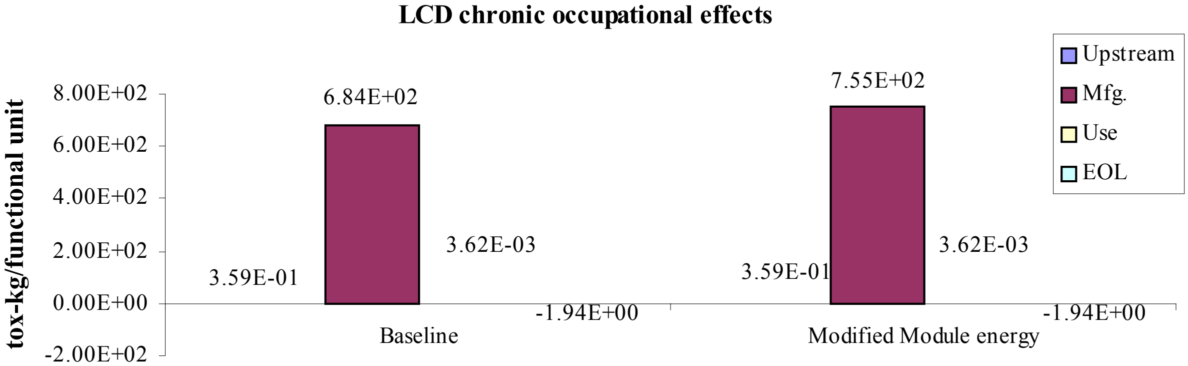

Figure 3-29. Chronic occupational effects: LCD baseline and modified module energy sensitivity results

3.4.4 Modified LCD EOL Dispositions Scenario

Finally, because very few desktop LCDs have reached their end of life, and usually only if they have been damaged in some way, very little is known about the EOL disposition of LCDs. In the baseline scenario it was assumed that a certain percent of EOL LCDs are incinerated, recycled, remanufactured, landfilled as solid waste, and landfilled as hazardous waste. (See Section 2.7.3 and Appendix I for an explanation of how EOL disposition percentages were determined.) To address uncertainties in the allocation of disposition percentages, this sensitivity analysis qualitatively evaluates a different set of final disposition numbers, as follows:

- change percent recycled from 15% to 0%,
- change percent remanufactured from 15% to 40%,
- change percent landfilled (solid waste) from 50% to 40%.
- do not change fraction incinerated (15%) or fraction sent to a hazardous waste landfill (5%).

Thus, under the modified EOL disposition scenario, recycling and solid waste landfilling impacts would decrease, remanufacturing impacts would increase, and incineration and hazardous waste landfilling impacts would not change. However, in attempts made to obtain remanufacturing data, it was found that remanufacturing processes spanned a wide range of activities, from as little as replacing button tops to as extensive as testing and replacing PWBs or transformers. Given the broad range of possibilities, and because few desktop LCDs have reached their end of life, no single set of operations could be identified to adequately represent remanufacturing activities that could be incorporated in our model. Remanufacturing data were, therefore, excluded from the assessment.

As shown in the baseline LCIA results (Section 3.3), LCD EOL dispositions have little effect on overall life-cycle impacts under the baseline scenario. In fact, the only impact categories in which an EOL process was a top contributor to overall impacts were the hazardous waste landfill use impact category, where the portion of a monitor landfilled contributed 97% of impacts, and the solid waste landfill use category, where the portion of a monitor landfilled contributed 3.5% of impacts. As noted above, hazardous waste landfill use impacts would not change under the modified LCD EOL dispositions scenario, but solid waste landfill impacts would be expected to decrease slightly. In a preliminary quantitative analysis of this scenario, LCD life-cycle solid waste landfill impacts were found to decrease less than one percent, and life-cycle impacts in other impact categories decreased less than 0.1%. Thus, the modified LCD EOL dispositions scenario would have only a minor effect on LCD life-cycle impacts and would not change comparative CRT and LCD results.

3.4.5 Summary of CRT and LCD Sensitivity Analysis Results

The results of the sensitivity analyses are useful to manufacturers who want to understand how uncertainty in the inventory affects impacts. This information can be used to identify areas for additional study or potential improvement opportunities. As discussed in Sections 3.4.1 through 3.4.2, it appears that CRT life-cycle impacts are highly sensitive to the glass energy data, and less sensitive to the lifespan assumptions (lifespan assumptions greatly affect the magnitude of CRT life-cycle impacts, but they do not greatly affect the distribution of impacts among life-cycle stage). LCD impacts are less sensitive to the glass energy data and in fact are not greatly affected by any of the sensitivity analysis scenarios, except the longer lifespan under the manufactured life scenario.

Sensitivity results are also useful to interested members of the public who may be evaluating the relative impacts of different monitor types and are interested in whether the CRT or LCD has greater life-cycle impacts in any given impact category. Table 3-62 presents the monitor type with greatest impacts by impact category and by scenario. This information helps us determine whether major assumptions (e.g., the monitor lifespan and LCD EOL distribution assumptions) or uncertain data (e.g., glass energy data and LCD monitor manufacturing energy) are driving results. As shown in the table, the modified glass energy scenario is the only scenario that significantly changes the results from the baseline CRT and LCD comparative results. Under this scenario, life-cycle impact results in seven categories reverse direction from the baseline assessment, such that the LCD has greater impacts than the CRT. Therefore, under this scenario, a total of nine out of 20 categories are greater for the LCD than the CRT, compared to two out of 20 categories under the baseline scenario. The only other scenario that affects these results is the manufactured life scenario, when impacts in the water eutrophication category are greater for the CRT than the LCD.

Table 3-62. Summary of CRT and LCD LCIA results

Impact category	**Monitor type with greatest impacts by scenario**				
	Baseline	**Manu-factured life**	**Modified glass energy**	**Modified LCD module energy**	**Modifed LCD EOL distribution**[a]
Renewable resource use	CRT	CRT	CRT	CRT	CRT
Nonrenewable resource use	CRT	CRT	LCD	CRT	CRT
Energy use	CRT	CRT	CRT	CRT	CRT
SW landfill use	CRT	CRT	CRT	CRT	CRT
HW landfill use	CRT	CRT	CRT	CRT	CRT
RW landfill use	CRT	CRT	CRT	CRT	CRT
Global warming	CRT	CRT	LCD	CRT	CRT
Ozone depletion [b]		[b] [b]	[b] [b]		
Photochemical smog	CRT	CRT	LCD	CRT	CRT
Acidification	CRT	CRT	CRT	CRT	CRT
Air particulates	CRT	CRT	CRT	CRT	CRT
Water eutrophication	LCD	CRT	LCD	LCD	LCD
Water quality, BOD	CRT	CRT	LCD	CRT	CRT
Water quality, TSS	CRT	CRT	LCD	CRT	CRT
Radioactivity	CRT	CRT	CRT	CRT	CRT
Chronic health effects, occupational	CRT	CRT	LCD	CRT	CRT
Chronic health effects, public	CRT	CRT	CRT	CRT	CRT
Aesthetics (odor)	CRT	CRT	LCD	CRT	CRT

Table 3-62. Summary of CRT and LCD LCIA results

Impact category	**Monitor type with greatest impacts by scenario**				
	Baseline	**Manu-factured life**	**Modified glass energy**	**Modified LCD module energy**	**Modifed LCD EOL distribution**[a]
Aquatic toxicity	LCD	LCD	LCD	LCD	LCD
Terrestrial toxicity	CRT	CRT	CRT	CRT	CRT

[a] Based on a qualitative evaluation, not quantitative results.

[b] CRT impacts are greater than LCD impacts in this category when all data are included in the inventories, including data for substances that have been phased out. However, LCD impacts are greater than CRT impacts when phased out substances are removed from the inventories (see Section 3.3.6).

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