Land Quality Division

DEQ

State of Oregon
Department of Environmental Quality

Life Cycle Assessment of Drinking Water Systems: Bottle Water, Tap Water, and Home/Office Delivery Water

Revised Final Peer-Reviewed LCA Report

Prepared for DEQ by
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PREFACE

The report that follows is a Life Cycle Assessment (LCA) of three types of drinking water systems – water packaged in disposable bottles, tap water consumed from reusable drinking containers, and home/office delivery water consumed from reusable drinking containers. Funding for this project was provided by the Oregon Department of Environmental Quality (DEQ).

At ERG, the project was managed by Beverly J. Sauer, who served as primary life cycle analyst. Greg Schivley and Ann Marie Molen assisted with research tasks and development of the report appendices. Chris Dettore, a graduate student at the University of Michigan, provided assistance with research and contribution analysis tasks, with oversight by Dr. Greg Keoleian of the University of Michigan Center for Sustainable Systems.

ERG gratefully acknowledges significant contributions to this project by Abby Boudoris, David Allaway, and Jordan Palmeri of Oregon DEQ, and Todd Jarvis, Associate Director of the Institute for Water and Watersheds at Oregon State University. Their efforts added significantly to the quality of the report.

The project was peer reviewed by an expert panel consisting of Beth Quay, an independent consultant with expert knowledge of bottling systems (serving as review chair), Dr. David Allen of the University of Texas, and David Cornell, an independent consultant with expert knowledge of PET container systems. The revisions made in response to the peer review panel’s insightful comments added greatly to the quality and credibility of this final report.

This study was conducted for DEQ by ERG as an independent contractor. The findings and conclusions presented in this report are strictly those of ERG. ERG makes no statements nor supports any conclusions other than those presented in this report.

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EXECUTIVE SUMMARY

INTRODUCTION

Bottled water offers consumers a clean, portable supply of drinking water for consumption at home or away from home. Some disposable water bottles are recyclable, and lightweighting of bottles and bottled water packaging have reduced the amount of packaging waste associated with bottled water consumption. However, bottled water is frequently consumed at away from home locations where access to container recycling may be limited. In addition, while recycling of postconsumer bottles and packaging reduces consumption of virgin material resources, other resources are used and wastes created when packaging is manufactured and bottled water is transported.

Consumers have other drinking water options that do not involve disposable containers. These include consumption of tap water from a container that can be washed and reused many times, or consumption of water from a home/office delivery system with the water dispensed into a reusable drinking container. However, while reusable systems require less use and disposal of material, these systems require washing of containers between uses, and in the case of HOD systems, transportation of the containers to and from the filler. These processes incur environmental burdens that may be higher or lower than the burdens for disposable container systems.

Life Cycle Assessment (LCA) has been recognized as a scientific method for making comprehensive, quantified evaluations of the environmental benefits and tradeoffs for the entire life cycle of a product system, beginning with raw material extraction and continuing through disposition at the end of its useful life. This LCA evaluates the environmental burdens for disposable and reusable systems for delivering drinking water.

PURPOSE OF THE STUDY

This LCA was commissioned by the Oregon Department of Environmental Quality (OR DEQ) to evaluate the environmental implications of various systems for delivery and consumption of drinking water, including bottled water, tap water consumed from reusable containers, and home/office delivery (HOD) water consumed from reusable containers. The analysis includes water processing, production of containers and packaging materials, filling, transport, and end-of-life management of containers and packaging. The analysis also looks at transportation of bottled water imported from several foreign locations.

This study uses container weight and packaging data obtained by weighing purchased samples of various brands of bottled water and reusable drinking containers,[1]

[1] Supplemented with information from a published article about bottle weight trends: Bauerlein, Valerie. “Pepsi to Pare Plastic for Bottled Water.” Wall Street Journal. March 25, 2009.

and import distances are estimated based on the locations of several countries where popular brands of imported water are bottled. The companies producing these brands of bottled water did not participate directly in this study, and their specific operations may be significantly different from the data sets and modeling assumptions used in this report. **The results presented in this report are not intended to be used to represent specific brands of bottled water or reusable containers available in the marketplace.** For example, a scenario shown for water imported from Fiji is one of several import scenarios developed using purchased container weights and estimates of transportation distances from bottling location to Oregon; however, the results for this scenario are **not** intended to be used to represent the specific products or operations of FIJI Water Company LLC, since no data from FIJI were collected for this study.

INTENDED USE

The primary intended use of the study results is to inform DEQ about the environmental burdens and tradeoffs associated with various options for providing drinking water to consumers and behavioral choices of consumers. DEQ is also interested in better understanding the environmental burdens and tradeoffs of end-of-life management options (recycling, composting, landfilling, etc.).

This analysis contains comparative statements about the drinking water subscenarios analyzed. These statements are supported by the data presented in this report and apply to the systems analyzed in this study. Because DEQ will make the results of this study, including comparative statements, publicly available, this report is being peer reviewed in accordance with ISO standards for life cycle assessment.[2]

SYSTEMS STUDIED

The following types of drinking water systems are analyzed in this study:

- Bottled water packaged in and consumed from individual disposable bottles:
    - Virgin polyethylene terephthalate (PET) bottles (16.9 ounce, 8 ounce, and one liter)
    - PET bottles with a mix of virgin and recycled content (16.9 ounce)
    - Bottles made of virgin polylactide (PLA) resin derived from corn (16.9 ounce)
    - Glass bottles with a mix of virgin and recycled content (12 ounce)
- Tap water consumed from reusable containers:
    - Virgin aluminum bottle with plastic closure (20 ounce)
    - Virgin steel bottle with plastic closure (27 ounce)
    - Virgin plastic bottle with plastic closure (32 ounce)

[2] International Standards Organization. ISO 14040:2006 Environmental management—Life cycle assessment—Principles and framework, ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines.

  - o Drinking glass with a mix of virgin and recycled content (16 ounce)
- Home/office delivery (HOD) water consumed from reusable containers
  - o Virgin polycarbonate bottles
  - o Virgin PET bottles
  - o Same reusable containers listed under the Tap system.

Within these three general drinking water scenarios, a number of subscenarios were analyzed to evaluate the results for variations in container sizes, weights, transportation distances, recycled content and recycling rates, and many other variables. Forty-eight subscenarios were evaluated in all: 25 bottled water subscenarios (20 for PET bottles, 4 for PLA, 1 for glass), 12 subscenarios for tap water consumption using a variety of reusable drinking containers, and 11 subscenarios for HOD water consumed from reusable containers. Of the bottled water subscenarios, 5 evaluated long-distance transport of water from another country or the Eastern U.S. to Oregon.

FUNCTIONAL UNIT

In a life cycle study, systems are evaluated on the basis of providing a defined function (called the **functional unit**). The function of each system analyzed in this report is to deliver drinking water to consumers. The functional unit selected for this analysis is delivering 1,000 gallons of drinking water to a consumer, including use of a bottle or reusable drinking container, and end-of-life management of the containers and packaging. To provide some perspective, 1,000 gallons is the amount of water a person would consume in about 5.5 years if they drank eight 8-ounce servings of water a day.

The functional equivalence is based on delivering drinking water that meets water quality standards set by the Food and Drug Administration (FDA), EPA, and state governments. The scope of the analysis does not include evaluating other differences in the quality of the water (e.g., taste, fluoride or mineral content, etc.) or temperature of the water, or any potential health impacts that may be associated with the use of specific water container materials. Each subscenario evaluated clearly indicates whether the results included chilling of the water, and if so, the chilling method used. No carbonated or flavored waters were evaluated.

SCOPE AND BOUNDARIES

This study is a complete life cycle assessment (LCA) as defined in the ISO standards 14040 and 14044. As such, the study includes definition of goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of results.

The analysis includes all steps in the production of each drinking water container system, from extraction of raw materials through production of the materials used in the containers, fabrication of finished containers and closures, and transport to filling locations. Treatment of municipal drinking water and additional processing steps used to purify bottled municipal water and natural water such as spring water are included in the analysis. Bottle filling and washing operations are included, as is production of secondary packaging used for shipment of filled containers, distribution of filled containers, washing of reusable containers, and end-of-life management of containers and associated packaging components. Various options for chilling water are also included in the model, including home refrigeration, use of ice, and HOD chiller units.

All washing of reusable personal drinking containers in this study is modeled based on use of a residential dishwasher, which is expected to be the most common method used by consumers for washing of these containers. Containers may also be hand-washed; however, water and detergent use for hand washing can vary widely based on the practices of individual consumers. As a result, hand washing of containers can be either more or less burdensome than machine washing.

The scope of the study did not include analysis of scenarios for HOD and tap water consumed from disposable cups, nor did the study include any scenarios in which disposable drinking water bottles sold filled with water were refilled by consumers and used as a reusable drinking container. Additional at-home purification of tap water, such as use of tap water filters, was not included in the scope of the analysis. The scope of the analysis did not include greenhouse gas effects of direct and indirect land use changes that may be associated with corn growing for PLA production.

In Oregon, municipal solid waste (MSW) that is not recovered for recycling or composting is managed 93 percent by weight to landfill (LF), 6 percent by weight to waste-to-energy (WTE) combustion, and 1 percent by combustion without energy recovery, as documented in Appendix J. An energy credit is given for material that is managed by WTE combustion, based on the amount of each material burned, its heating value, and the efficiency of converting the gross heat of combustion to useful energy.

The end-of-life emissions results take into account the effects of combustion, decomposition, and energy recovery, including estimates of release of carbon dioxide from combustion of materials and methane from decomposition of degradable landfilled material, emission credits for avoided grid electricity displaced by electricity generated from WTE operation and from landfill gas combustion, and carbon sequestration in landfilled biomass-derived material that does not decompose. The end-of-life modeling and recycling methodologies are described in Chapter 1. The LCI results are presented in Chapter 2.

In the scoping phase of this study, the U.S. EPA’s TRACI methodology was selected as the impact assessment methodology to be used, since it was developed to represent U.S. conditions (e.g., for fate and transport of chemical releases). Details of the LCIA are presented in Chapter 3.

DATA

Detailed descriptions of the data and assumptions used in the life cycle assessment are provided in the Appendices, a separate document. Wherever possible the study used Oregon-specific data and assumptions, including the following:

- Mix of fuels to produce electricity used for processes that occur in Oregon, including processing and filling operations for bottled water processed in Oregon; operation of pumps to deliver municipal tap water to Oregon homes or to pump well water; molding of plastic water bottles produced in Oregon; operation of home dishwashers used to clean reusable containers between uses, electricity use in washing operations for HOD bottles that are filled and circulated in Oregon;
- Transportation distances for bottled water;
- Mix of residential water from wells and municipal water supplies;
- Recycling rates for PET bottles, glass bottles, and corrugated packaging;
- Percentages of landfilling, waste-to-energy combustion, and combustion without energy recovery for municipal solid waste management of containers that are not recycled;
- Modes and distances for transport of postconsumer solid waste to landfill and combustion facilities;
- Management of landfill gas.

MAIN CONTRIBUTING FACTORS FOR EACH SYSTEM

The primary factors contributing to the results for the bottled water system include the following:

- Production of bottles accounts for the majority of energy consumption for all subscenarios except those involving long-distance transport. Scenarios for trucking water cross-country showed higher energy requirements than scenarios where water was transported longer distances by ocean and a shorter distance by truck.
- The energy requirements for bottled water delivered in the 8-ounce bottle (scenario 5) are higher than the energy to deliver water in larger bottles because the smaller bottle has a higher ratio of bottle weight to weight of water in the bottle.
- In addition to the bottles themselves, the bottle lids and secondary packaging make significant contributions to the energy results. On average across all subscenarios, production of caps and secondary packaging each accounted for 12 percent of total energy.
- The choice of recycling allocation methodology for LCI analysis also can have a significant effect on the results. Use of an open-loop recycling allocation divides the burdens for material production and disposal between the product uses of the material, while alternative “cut-off” recycling allocations assign material production and disposal burdens to

either the system first using the virgin material or to the system using the recycled material.

For tap water consumed from reusable containers, results are driven by washing of the container (including energy use for heating the water) and variations in the use of the container that affect the frequency of washing.

- The number of drinking container washings per thousand gallons of water consumed varies inversely with the size of the containers, the number of times the container is filled before washing, and the number of days the container is used before washing. The drinking glass system (scenario 18) has the lowest energy use for container manufacture but has the highest washing requirements because it is smaller than the other reusable containers so that the container must be filled (and washed) more times per 1,000 gallons consumed.
- Doubling the number of container fills between washings or washing the container every other day instead of daily reduces the washing requirements by half.
- Efficient use of the dishwasher is also important. The highest results for the tap water system are for the scenario in which containers are washed daily in a dishwasher with a high water consumption rate that is run when it is half full.

For HOD water consumed from reusable containers, the three life cycle stages that consistently making the largest contributions to overall energy use are transportation of HOD containers (delivery of filled HOD containers and backhauling of empty containers to be washed and refilled), home washing of the reusable drinking containers, and chilling of the HOD water using a chilling base unit.

- Distribution of HOD containers includes transportation of filled containers from bottler to HOD distributor, dropping off filled bottles and picking up empties on delivery route, and backhauling empties to filling location for refilling. Distribution accounts for about 25 percent of total energy requirements for the subscenarios evaluated.
- Observations for washing of the reusable drinking container are the same as described above for the tap water system. Industrial washing of the HOD bottles makes a much smaller contribution to the overall results than does home washing of the individual drinking container.
- Chilling of drinking water is not required in order to maintain the quality of drinking water. While chilling of bottled water and tap water is done at the discretion of the consumer, HOD water is most commonly dispensed from a base unit that chills the water, so chilling energy use was included in all the HOD scenarios. This is a difference from the modeling of the bottled water and tap water scenarios, where most of the subscenarios did not include chilling. Energy for chilling of HOD water ranges from 20 to 40 percent of total energy for HOD systems and accounts for around 30

percent of total energy for most HOD subscenarios. Chilling results are shown separately in the results tables so that results for HOD systems without chilling can be compared to results for unchilled bottled and tap water.

OBSERVATIONS AND CONCLUSIONS

Some general observations and conclusions can be made based on the results for the full range of subscenarios evaluated, which include combinations of parameters selected to represent “best” and “worst” cases for each system. It should be noted that the “best” and “worst” case subscenarios include future lightweighting and increased recycling scenarios. The full range of results also includes some subscenarios that account for a small percentage of total Oregon bottled water consumption (e.g., imported water packaged in glass bottles). The reader is encouraged to refer to the figures in Chapters 2 and 3 for results for individual scenarios for each system and the figures in Chapter 4 for the ranges of results for individual impacts across all subscenarios evaluated.

Energy Results

Energy comparisons between the different drinking water systems can be summarized as follows:

- All tap and HOD scenarios show lower energy than all long-haul water scenarios.
- The “best case” results for Oregon bottled water (excluding long-haul water) are for a future lightweighted bottle not currently in the marketplace, combined with 100% bottle recycling. When *existing* Oregon bottled water subscenarios are compared to tap subscenarios, the energy for tap subscenarios is lower in all cases.
- When existing Oregon bottled water subscenarios are compared to HOD subscenarios, there is overlap in many cases so that neither system can generally be considered to have lower energy results.
- Assuming a consumer’s container washing practices are not influenced by the type of water served in the container, tap water systems have lower energy requirements than HOD water systems.

Solid Waste Results

As would be expected, the HOD and tap water systems do not produce much solid waste compared to the majority of the bottled water scenarios, since the tap and HOD systems utilize drinking water containers that are used many times over their useful life. The HOD bottles are also refilled and reused multiple times before they are retired from service and recycled; however, the solid waste results for the HOD systems do include the weight of disposed HOD plastic caps that are assumed to be replaced after each use cycle of an HOD bottle.

The choice of recycling allocation method has a significant influence on the solid waste weight and solid waste volume comparisons. The majority of subscenarios used an open-loop recycling methodology (designated method 1), in which half of the disposal burdens for the recycled bottles are allocated to the bottle system and half to the next system using the recycled material. The other recycling methods evaluated (designated methods 2 and 3) allocate *all* disposal burdens for recycled material to the next system using the recycled material, so the subscenarios using methods 2 and 3 show lower solid waste results than the subscenarios using method 1. A detailed description of the recycling methodologies can be found in the Postconsumer Recycling Methodology section of Chapter 1.

The following solid waste observations can be made:

- In nearly all solid waste comparisons, both the tap and HOD systems have lower solid waste than the bottled water systems (long-haul and Oregon bottled water), although there are a few exceptions. The HOD worst case scenario overlaps with several Oregon bottled water solid waste subscenarios. Excluding the HOD worst case, the only other comparisons where bottled water solid wastes are lower than tap and HOD solid wastes are for the PLA bottle at 100% composting and the future lightweighted PET bottle at 100% recycling.
- Assuming a consumer's container washing practices are not influenced by the type of water served in the container, tap water systems have lower solid waste requirements than all HOD subscenarios except when compared to the HOD best case scenario.

Impact Categories

Rather than describing each impact category individually, this section describes general trends observed in the impact figures in Chapter 4. The reader is encouraged to refer to Chapter 4 to view results for individual impact categories. Environmental impact results can be summarized as follows:

Comparison of Long-haul Bottled Water and Oregon Bottled Water Systems. Within the bottled water subscenarios evaluated, the ranges of impact results for long-haul bottled water and Oregon bottled water overlap or show small gaps for most impact categories. It should be noted that differences in impacts for long-haul and Oregon bottled water are due not only to differences in transportation but also to differences in the types and weights of bottles used for domestic and imported water.

Comparison of Tap and Bottled Water Systems. For the subscenarios evaluated in this study, all tap subscenario results are lower in all impact categories compared to all long-haul bottle subscenarios. When comparing tap system results to Oregon bottled water results, the tap system subscenarios evaluated all have lower impacts than *existing* Oregon bottled water scenarios. The *future* lightweighted PET bottle combined with very high bottle recycling rates has the potential to compare favorably with tap scenarios with inefficient container washing practices.

Comparison of HOD and Bottled Water Systems. For the subscenarios evaluated in this study, all HOD subscenario results are lower in all impact categories compared to the long-haul bottle subscenarios. When comparing HOD subscenario results and the Oregon bottled water subscenario results, there are many subscenarios where there is overlap between HOD and Oregon bottled water results, even when the best and worst case scenarios are excluded for each system. Therefore, no general statements can be made about which of these systems has lower environmental impacts.

CHAPTER 1

LIFE CYCLE INVENTORY METHODOLOGY

OVERVIEW

This life cycle inventory (LCI) quantifies the total energy requirements, energy sources, atmospheric pollutants, waterborne pollutants, and solid waste resulting from the life cycle of several types of drinking water systems, including bottled water, tap water, and home office delivery (HOD) water. The bottled water is assumed to be consumed directly from the bottle, while the tap and HOD water is assumed to be dispensed into reusable containers from which the water is consumed. The tap and HOD system analyses include the life cycle of the reusable containers. The purpose of this chapter is to define the life cycle methodology used to develop the results presented in Chapter 2.

A life cycle inventory quantifies the energy consumption and environmental emissions (i.e., atmospheric emissions, waterborne emissions, and solid wastes) for a given product based upon the study boundaries established. Figure 1-1 illustrates the general approach used in a full LCI analysis.

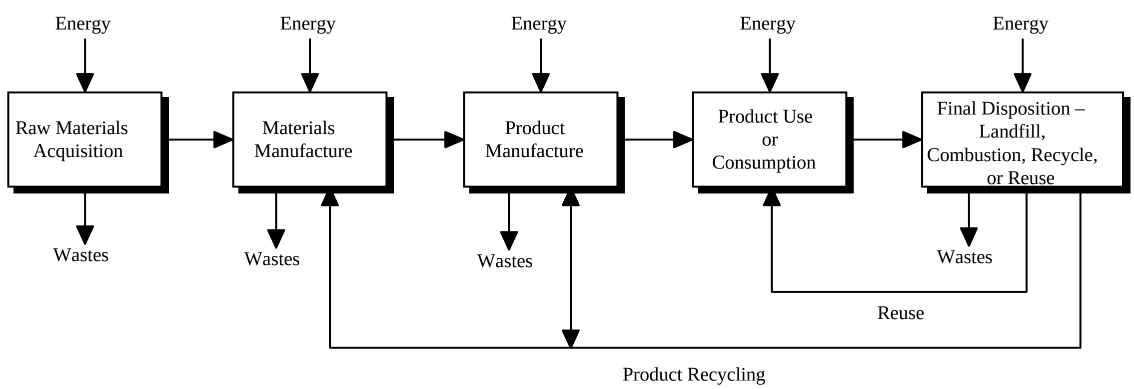

Figure 1-1. General materials flow for "cradle-to-grave" analysis of a product system.

Study Scope and Boundaries

This LCI encompasses the following steps in the life cycle of each drinking water system studied:

- Raw material extraction (e.g., extraction of petroleum and natural gas as feedstocks for plastic resins; growing corn used as a feedstock for polylactide resin, commonly referred to as PLA)
- Processing and fabrication steps to transform raw materials into containers and closures (water bottles, HOD bottles, reusable containers)

- Manufacture of materials used to package containers for retail shipment (corrugated trays, plastic film)
- Water treatment processes
- Container filling and washing operations (including industrial washing of HOD bottles and home washing of reusable drinking vessels)
- Distribution of filled containers
- Optional processes for chilling water
- End-of-life management of containers and packaging.

The LCI quantifies energy and resource use, solid wastes, and individual atmospheric and waterborne emissions for the life cycle stages listed above. Because of large uncertainties about the emissions resulting from waste to energy (WTE) combustion of containers and packaging and from decomposition of these materials in landfills, estimated end-of-life results are shown separately in the tables and figures. For WTE combustion of system components and for combustion of landfill gas with energy recovery, an emission credit is given for the equivalent amount of grid electricity displaced by the recovered energy. More details on the approach used for estimating end of life emissions and credits are provided at the end of this chapter in the section Methodological Decisions.

LIFE CYCLE INVENTORY METHODOLOGY

Key elements of the LCI methodology include the study boundaries, resource inventory (raw materials and energy), emissions inventory (atmospheric, waterborne, and solid waste), and disposal practices.

In the early 1970s, Franklin Associates developed a methodology for performing comprehensive environmental inventories called Resource and Environmental Profile Analyses, or REPA studies. This type of analysis later became widely known under the name Life Cycle Inventory. The life cycle inventory methodology has been documented for the United States Environmental Protection Agency and is incorporated in the EPA report **Product Life-Cycle Assessment Inventory Guidelines and Principles**. The data presented in this report were developed using this methodology, which has been in use for over 30 years and is consistent with ISO standards for life cycle assessment published in ISO 14040 and 14044.

Figure 1-2 illustrates the basic approach to data development for each major process in an LCI analysis. This approach provides the essential building blocks of data used to construct a complete resource and environmental emissions inventory profile for the entire life cycle of a product. Using this approach, each individual process included in the study is examined as a closed system, or “black box”, by fully accounting for all resource inputs and process outputs associated with that particular process. Resource inputs accounted for in the LCI include raw materials and energy use, while process outputs accounted for include products manufactured and environmental emissions to land, air, and water.

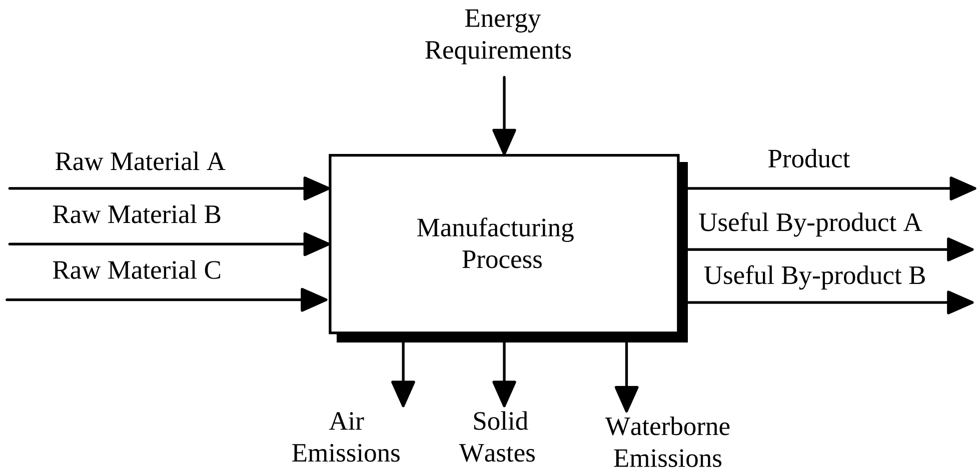

Figure 1-2. "Black box" concept for developing LCI data.

For each process included in the study, resource requirements and environmental emissions are determined and expressed in terms of a standard unit of output. A standard unit of output is used as the basis for determining the total life cycle resource requirements and environmental emissions of a product.

Material Requirements

Once the LCI study boundaries have been defined and the individual processes identified, a material balance is performed for each individual process. This analysis identifies and quantifies the input raw materials required per standard unit of output, such as 1,000 pounds, for each individual process included in the LCI. The purpose of the material balance is to determine the appropriate weight factors used in calculating the total energy requirements and environmental emissions associated with each process studied. Energy requirements and environmental emissions are determined for each process and expressed in terms of the standard unit of output.

Once the detailed material balance has been established for a standard unit of output for each process included in the LCI, a comprehensive material balance for the entire life cycle of each product system is constructed. This analysis determines the quantity of materials required from each process to produce and dispose of the required quantity of each system component and is typically illustrated as a flow chart. Data must be gathered for each process shown in the flow diagram, and the weight relationships of inputs and outputs for the various processes must be developed.

Energy Requirements

The average energy requirements for each process identified in the LCI are first quantified in terms of fuel or electricity units, such as cubic feet of natural gas, gallons of diesel fuel, or kilowatt-hours (kWh) of electricity. The fuel used to transport raw materials to each process is included as a part of the LCI energy requirements. Transportation energy requirements for each step in the life cycle are developed in the conventional units of ton-miles by each transport mode (e.g. truck, rail, barge, etc.). Government statistical data for the average efficiency of each transportation mode are used to convert from ton-miles to fuel consumption.

Once the fuel consumption for each industrial process and transportation step is quantified, the fuel units are converted from their original units to an equivalent Btu value based on standard conversion factors.

The conversion factors have been developed to account for the energy required to extract, transport, and process the fuels and to account for the energy content of the fuels. The energy to extract, transport, and process fuels into a usable form is labeled **precombustion energy.** For electricity, precombustion energy calculations include adjustments for the average efficiency of conversion of fuel to electricity and for transmission losses in power lines based on national averages.

The LCI methodology assigns a fuel-energy equivalent to raw materials that are derived from fossil fuels. Therefore, the total energy requirement for coal, natural gas, or petroleum based materials includes the fuel-energy of the raw material (called **energy of material resource** or inherent energy). In this study, this applies to the crude oil and natural gas used to produce the plastic resins. No fuel-energy equivalent is assigned to combustible materials, such as wood, that are not major fuel sources in North America.

The Btu values for fuels and electricity consumed in each industrial process are summed and categorized into an energy profile according to the six basic energy sources listed below:

- Natural gas
- Petroleum
- Coal
- Nuclear
- Hydropower
- Other

The "other" category includes sources such as solar, biomass and geothermal energy. Also included in the LCI energy profile are the Btu values for all transportation steps and all fossil fuel-derived raw materials. Energy results for the drinking water systems studied in this analysis are provided in Chapter 2.

Environmental Emissions

Environmental emissions are categorized as atmospheric emissions, waterborne emissions, and solid wastes and represent discharges into the environment after the effluents pass through existing emission control devices. Similar to energy, environmental emissions associated with processing fuels into usable forms are also included in the inventory. When it is not possible to obtain actual industry emissions data, published emissions standards are used as the basis for determining environmental emissions.

The different categories of atmospheric and waterborne emissions are not totaled in this LCI because it is widely recognized that various substances emitted to the air and water differ greatly in their effect on the environment.

Atmospheric Emissions. These emissions include substances classified by regulatory agencies as pollutants, as well as selected non-regulated emissions such as carbon dioxide. For each process, atmospheric emissions associated with the combustion of fuel for process or transportation energy, as well as any emissions released from the process itself, are included in this LCI. The amounts reported represent actual discharges into the atmosphere after the effluents pass through existing emission control devices. Some of the more commonly reported atmospheric emissions are: carbon dioxide, carbon monoxide, non-methane hydrocarbons, nitrogen oxides, particulates, and sulfur oxides. The emissions results discussion in Chapter 2 focuses on greenhouse gas emissions, expressed in pounds of carbon dioxide equivalents.

Waterborne Emissions. As with atmospheric emissions, waterborne emissions include all substances classified as pollutants. The values reported are the average quantity of pollutants still present in the wastewater stream after wastewater treatment and represent discharges into receiving waters. This includes both process-related and fuel-related waterborne emissions. Some of the most commonly reported waterborne emissions are: acid, ammonia, biochemical oxygen demand (BOD), chemical oxygen demand (COD), chromium, dissolved solids, iron, and suspended solids.

Solid Wastes. This category includes solid wastes generated from all sources that are landfilled or disposed of in some other way, such as incineration with or without energy recovery. These include industrial process- and fuel-related wastes, as well as the packaging components that are disposed when a container of product is emptied. Examples of industrial process wastes are residuals from chemical processes and manufacturing scrap that is not recycled or sold. Examples of fuel-related solid wastes are ash generated by burning coal to produce electricity, or particulates from fuel combustion that are collected in air pollution control devices.

LCI PRACTITIONER METHODOLOGY VARIATION

There is general consensus among life cycle practitioners on the fundamental methodology for performing LCIs.[3] However, for some specific aspects of life cycle inventory, there can be variations in the methodology used by experienced practitioners. These areas include the method used to allocate energy requirements and environmental releases among more than one useful product produced by a process, the method used to account for the energy contained in material feedstocks, and the methodology used to allocate environmental burdens for postconsumer recycled content and end-of-life recovery of materials for recycling. LCI practitioners vary to some extent in their approaches to these issues. The following sections describe the approach to each issue used in this study.

Co-product Credit

One unique feature of life cycle inventories is that the quantification of inputs and outputs are related to a specific amount of product from a process. However, it is sometimes difficult or impossible to identify which inputs and outputs are associated with individual products of interest resulting from a single process (or process sequence) that produces multiple useful products. The practice of allocating inputs and outputs among multiple products from a process is often referred to as "co-product credit"[4] or "partitioning"[5].

Co-product credit is done out of necessity when raw materials and emissions cannot be directly attributed to one of several product outputs from a system. It has long been recognized that the practice of giving co-product credit is less desirable than being able to identify which inputs lead to particular outputs. In this study, co-product allocations are necessary because of multiple useful outputs from some of the "upstream" chemical processes involved in producing the resins used to manufacture plastic packaging components.

Franklin Associates follows the guidelines for allocating co-product credit shown in the ISO 14044:2006 standard on life cycle assessment requirements and guidelines. In this standard, the preferred hierarchy for handling allocation is (1) avoid allocation where possible, (2) allocate flows based on direct physical relationships to product outputs, (3) use some other relationship between elementary flows and product output. No single allocation method is suitable for every scenario. How product allocation is made will vary from one system to another but the choice of parameter is not arbitrary. ISO 14044

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3 International Standards Organization. ISO 14040:2006 Environmental management—Life cycle assessment—Principles and framework, ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines.

4 Hunt, Robert G., Sellers, Jere D., and Franklin, William E. **Resource and Environmental Profile Analysis: A Life Cycle Environmental Assessment for Products and Procedures.** Environmental Impact Assessment Review. 1992; 12:245-269.

5 Boustead, Ian. **Eco-balance Methodology for Commodity Thermoplastics.** A report for The Centre for Plastics in the Environment (PWMI). Brussels, Belgium. December, 1992.

section 4.3.4.2 states "The inventory is based on material balances between input and output. Allocation procedures should therefore approximate as much as possible such fundamental input/output relationships and characteristics."

Some processes lend themselves to physical allocation because they have physical parameters that provide a good representation of the environmental burdens of each co-product. Examples of various allocation methods are mass, stoichiometric, elemental, reaction enthalpy, and economic allocation. Simple mass and enthalpy allocation have been chosen as the common forms of allocation in this analysis. However, these allocation methods were not chosen as a default choice, but made on a case by case basis after due consideration of the chemistry and basis for production.

In the sequence of processes used to produce resins that are used in the plastic containers and closures, some processes produce material or energy co-products. When the co-product is heat or steam or a co-product sold for use as a fuel, the energy content of the exported heat, steam, or fuel is shown as an energy credit for that process. When the co-product is a material, the process inputs and emissions are allocated to the primary product and co-product material(s) on a mass basis. (Allocation based on economic value can also be used to partition process burdens among useful co-products; however, this approach is less preferred under ISO life cycle standards, as it depends on the economic market, which can change dramatically over time depending on many factors unrelated to the chemical and physical relationships between process inputs and outputs.)

In this study, corn grain is modeled as an input to production of PLA bottles. When corn grain is produced, corn stover (stalks and leaves) is coproduced. There are several ways in which corn stover can be managed. It may be left in the field to decompose, used for animal feed, or burned. In addition, there are some efforts to utilize corn stover as a source of biomass-derived energy. In this analysis, all of the corn growing burdens are allocated to the corn grain. The study used as the source of the corn growing data did not explicitly discuss the quantity of stover and whether it was treated as a co-product or as a waste[6]; the implicit assumption is that the stover was neither allocated any co-product benefits nor assigned any waste management burdens, which would correspond with a scenario in which the stover is simply left in the field to decompose.

In the sequence of process steps used to convert corn into starch at a wet mill, coproducts corn gluten and corn oil are also produced. For each process step at the mill, the energy and emissions are allocated to corn starch and other coproducts on a weight basis.

6 Shapouri et al 2002.

Energy of Material Resource

For some raw materials, such as petroleum, natural gas, and coal, the amount consumed in all industrial applications as fuel far exceeds the amount consumed as raw materials (feedstock) for products. The primary use of these materials in the marketplace is for energy. The total amount of these materials can be viewed as an energy pool or reserve. This concept is illustrated in Figure 1-3.

The use of a certain amount of these materials as feedstocks for products, rather than as fuels, removes that amount of material from the energy pool, thereby reducing the amount of energy available for consumption. This use of available energy as feedstock is called the **energy of material resource** (EMR) and is included in the inventory. The energy of material resource represents the amount the energy pool is reduced by the consumption of fuel materials as raw materials in products and is quantified in energy units.

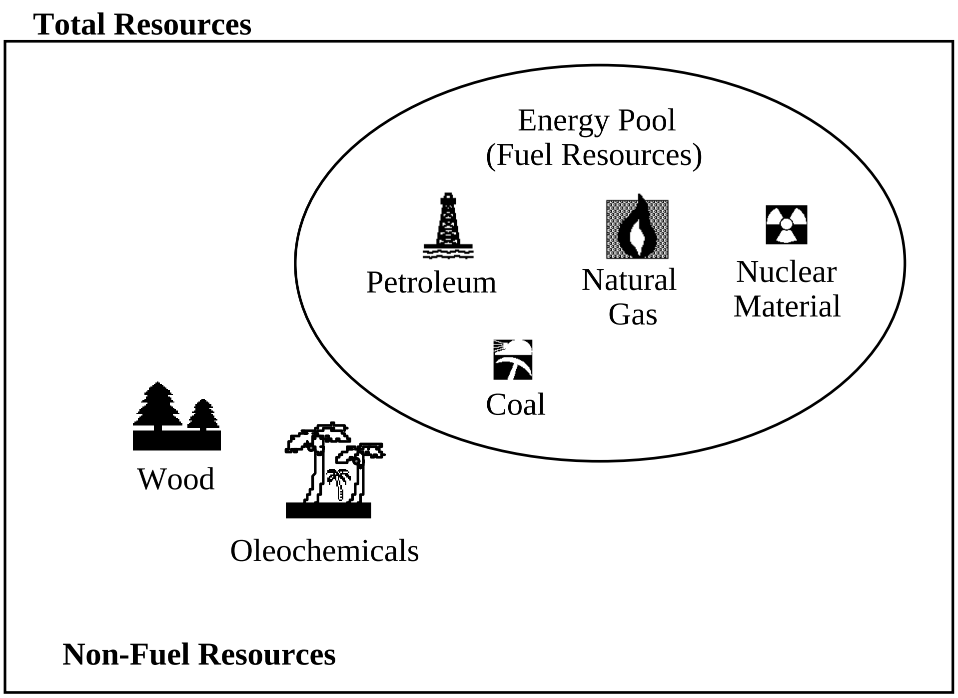

Figure 1-3. Illustration of the Energy of Material Resource Concept.

EMR is the energy content of the fuel materials *input* as raw materials or feedstocks. EMR assigned to a material is *not* the energy value of the final product, but is the energy value of the raw material at the point of extraction from its natural environment. For fossil fuels, this definition is straightforward. For instance, petroleum is extracted in the form of crude oil. Therefore, the EMR for petroleum is the higher heating value of crude oil.

Once the feedstock is converted to a product, there is energy content that could be recovered, for instance through combustion in a waste-to-energy waste disposal facility. The energy that can be recovered in this manner is always somewhat less than the feedstock energy because the steps to convert from a gas or liquid to a solid material reduce the amount of energy left in the product itself.

The materials which are primarily used as fuels (but that can also be used as material inputs) can change over time and with location. In the industrially developed countries included in this analysis, these materials are petroleum, natural gas, and coal. While some wood is burned for energy, the primary uses for wood are for products such as paper and lumber. Similarly, some oleochemical oils such as palm oils can be burned as fuel, often referred to as "bio-diesel." However, as in the case of wood, their primary consumption is as raw materials for products such as soaps, surfactants, cosmetics, etc.

At this time, the predominant use of biomass crops is for food or material use rather than as an energy resource. However, biomass is increasingly being used as feedstock for fuels, e.g., corn-derived ethanol and soy-derived biodiesel. At some point in the future, the energy of material resource methodology may be applied to biomass resources as well as fossil resources.

It should be noted that the results in the Chapter 2 energy tables include some process energy derived from wood wastes at paper mills and some energy recovery from WTE combustion of wood-derived paper containers and PLA containers, even though no energy of material resource is included for wood and corn under the energy of material resource accounting methodology described here.

Postconsumer Recycling Methodology

In this analysis, some drinking water containers are recycled at end of life. Some containers also have recycled content. When material is used in one system and subsequently recovered, reprocessed, and used in another application, there is a reduction in the total amount of virgin material that must be produced to fulfill the two systems' material needs. However, there are different methods by which the savings in virgin material production and disposal burdens can be assigned to the systems producing and using the recovered material. Material production, collection, reprocessing, and disposal burdens can be allocated over all the useful lives of the material, or boundaries can be drawn between each successive useful life of the material.

Because the choice of recycling allocation methodology can significantly influence the LCI results, several approaches are explored in this analysis, including sharing the burdens for a given quantity of resin equally between multiple uses of the resin (Method 1), assigning the resin production burdens to the system first using the virgin resin (Method 2), or transferring the resin production burdens from the system first using the virgin resin to the system that uses the recovered resin (Method 3). In all cases, the allocated burdens include the energy of material resource embodied in the plastic material.

Each recycling approach used in this analysis is described in more detail in the sections below. In these descriptions, the system from which the material is recovered is referred to as the "producer" system, and the system utilizing recovered material is referred to as the "user" system. It should be noted that all recycling allocations are based only on the burdens for the *resin material* and do not include any allocation of the burdens associated with fabricating the resin into a bottle or any other product. Thus, there are no inherent assumptions about the product in which resin is used before or after the resin's use in the bottle system.

Method 1: Open-loop Allocation. The recycling methodology designated method 1 in this analysis is an **open-loop allocation** approach. In this approach, all environmental burdens associated with a quantity of recycled material are shared equally between the systems producing and using the material, resulting in reduced burdens for both systems. The producer and user systems share the burdens for virgin material production, collection, reprocessing, and disposal, so that both systems share equally in the benefits of recycling.

For bottles that contain recycled material, the recycled resin content of the bottle comes into the bottle system with half of its virgin production burdens (as well as half of the burdens for collecting and reprocessing the material and disposing of the material at end of life). The other half is allocated to the original product system that used the material, which is outside the boundaries of this analysis. For example, if a bottle had recycled content "r", the recycled material in the bottle would carry half of the burdens required to produce, collect, reprocess, and dispose of that material, or r/2 * (V+PC+D), where "V" is virgin material production burdens, "PC" is postconsumer collection and reprocessing burdens, and "D" is disposal burdens. The virgin percentage of the bottle would carry full burdens for material production and disposal, or (1–r)*(V+D). Adding these together, the total virgin production burdens allocated to the recycled content bottle are (r/2)*V + (1-r)*V, or (1-r/2)*V. Similarly, the material disposal burdens allocated to the recycled content bottle are (r/2)*D + (1-r)*D, or (1-r/2)*D. The collection and reprocessing burdens for the recycled content allocated to the bottle are r/2*PC.

A similar allocation approach is used for virgin bottles that are recycled after use. If "R" percent of virgin bottles are recycled at end of life, with half the virgin burdens for the bottle material going to a subsequent use outside the boundaries of the bottle system, then the virgin burdens allocated to the bottle system for the recycled bottles are R/2*(V+ PC+D) for the bottles that are recycled + (1–R)*(V+D) for the material in the bottles that are not recycled. The total virgin production burdens allocated to the bottle are (R/2)*V+ (1-R)*V, or (1-R/2)*V, the allocated disposal burdens are (R/2)*D + (1-R)*D, or (1-R/2)*D, and the collection and reprocessing burdens are R/2*PC.

For bottles that contain recycled material *and* are recycled after use, allocation becomes more complicated. For an example of bottles with recycled content r *and* recycling rate R, the virgin burdens for the material *in* the bottle are (1-r/2)*(V), as described above. Some of these burdens must then be allocated to the next use of the material, using the (1–R/2) allocation. The net virgin burdens assigned to the bottle system, taking into account both the recycled content and the postconsumer recycling rate, are (1–r/2)*V*(1–R/2). The allocated disposal burdens are (1-r/2)*D*(1-R/2). The share of recycling burdens allocated to the bottle system is r/2*PC*R/2.

No further projections are made about the fate of the material after the end of its recycled use. For example, if a product made from recycled bottle material is subsequently recycled at the end of its life, then the material would have three uses rather than two. This analysis uses a conservative approach and takes into account only the *known* number of useful lives of the bottle material (i.e., one prior use for recycled material used in bottles that have recycled content; one subsequent use for bottle material that is recycled at end of life).

The other two recycling approaches are less complicated to model, as they draw boundaries between successive lives of the material, with burdens for specific steps allocated to either the producer system or the user system. When postconsumer material from one system is used in a second system, different perspectives can be taken as to whether the producer or user system deserves the credit for the reductions in virgin material production and material disposal due to recycling.

Method 2: User Credit Allocation. Recycling methodology 2 can be called the **user credit** method. In this approach the boundaries between successive uses of the material are drawn so that the system *using* the recycled material gets the credit for avoiding production of more virgin material. In method 2, all virgin material burdens for initially producing material are allocated to the first system using the material (e.g., a virgin water bottle), and the next system using the recovered material (resin from recovered bottles) takes all the burdens for collection and reprocessing of the material, as well as the burdens for disposing of the material (unless it is recycled again after use in the second system). The benefit to the producer system (in this example, the bottle system) is limited to avoided disposal burdens for the material that goes on to the secondary user. Using the same variables as above, the allocations are as follows:
For a bottle with recycled content r and recycling rate R, the virgin material production burdens assigned to the bottle are (1-r)*V, the recycling burdens are r*PC, and the disposal burdens are (1-R)*D.

Method 3: Producer Credit Allocation. Recycling method 3 can be referred to as the **producer credit** method. In this approach, the system *generating* the recovered material gets the credit for avoiding the need to produce more virgin material. Because the material is not disposed but goes on to a subsequent use, the producer system is assigned burdens for collecting and reprocessing the material in order to deliver it to the next user (in lieu of the burdens that would otherwise be incurred for disposing of the material). The virgin burdens for producing the material and the burdens for disposing of the material are transferred to the next system using the material, which may in turn pass these burdens on to a subsequent use if that product is recovered and recycled at end of life. Using the same variables as above, the allocations are as follows: For a bottle with recycled content r and recycling rate R, the virgin material production burdens assigned to the bottle are V*(1-R), the recycling burdens are R*PC, and the disposal burdens are D*(1-R).

System Expansion. Another approach that can be used to allocate burdens for coproducts or recycled products is system expansion, in which credit is given for a product or material that is displaced by the product or material of interest. In order to use system expansion, it is important to know the specific application that is being displaced, as different uses of material have different reprocessing requirements and different fabrication requirements. As noted previously, the recycling allocations in this analysis are applied only to the burdens associated with the resin material. The recycling allocations do not include additional processing to prepare the resin for a specific end use or fabricate it into a specific product (e.g., a food-grade application or production of carpet fiber) before or after its use in the bottle system, nor were any assumptions made about the previous or subsequent products in which the bottle resin would be used. The recycling burdens in this study are based on collection and mechanical recycling of PET bottles into "generic" clean flake, and not on displacement of any specific product.

DATA

The accuracy of the study is directly related to the quality of input data. The development of methodology for the collection of data is essential to obtaining quality data. Careful adherence to that methodology determines not only data quality but also objectivity. Data quality and uncertainty are discussed in more detail at the end of this section.

Data necessary for conducting this analysis are separated into two categories: **process-related data** and **fuel-related data**.

Process Data

Methodology for Collection/Verification. The process of gathering data is an iterative one. The data-gathering process for each system begins with a literature search to identify raw materials and processes necessary to produce the final product. The search is then extended to identify the raw materials and processes used to produce these raw materials. In this way, a flow diagram is systematically constructed to represent the production pathway of each system. Each process identified during the construction of the flow diagram is then researched to identify potential industry sources for data.

Confidentiality. Franklin Associates takes care to protect data that is considered confidential by individual data providers. This can be done by aggregating data with data sets from other sources for the same unit process or aggregating the data with other sequential life cycle unit processes. The appendices for this report (a separate document) present all data sets used in this analysis at the maximum level of detail possible while still protecting confidentiality.

Objectivity. Each unit process in the life cycle study is researched independently of all other processes. No calculations are performed to link processes together with the production of their raw materials until *after* data gathering and review are complete. This allows objective review of individual data sets before their contribution to the overall life cycle results has been determined. Also, because these data are reviewed individually, assumptions are reviewed based on their relevance to the process rather than their effect on the overall outcome of the study.

Data Sources. Data from credible published sources or licensable databases were used wherever possible in order to maximize transparency. For processes and materials where reliable current published data were not available, data sets from Franklin Associates' United States industry average database were used. This database has been developed over a period of years through research for many LCI projects encompassing a wide variety of products and materials. Another advantage of the database is that it is continually updated. For each ongoing LCI project, verification and updating is carried out for the portions of the database that are accessed by that project. Data sources used for this report are documented in the appendices.

Fuel Data

When fuels are used for process or transportation energy, there are energy and emissions associated with the production and delivery of the fuels as well as the energy and emissions released when the fuels are burned. Before each fuel is usable, it must be mined, as in the case of coal or uranium, or extracted from the earth in some manner. Further processing is often necessary before the fuel is usable. For example, coal is crushed or pulverized and sometimes cleaned. Crude oil is refined to produce fuel oils, and "wet" natural gas is processed to produce natural gas liquids for fuel or feedstock.

To distinguish between environmental emissions from the combustion of fuels and emissions associated with the production of fuels, different terms are used to describe the different emissions. The combustion products of fuels are defined as **combustion data**. Energy consumption and emissions which result from the mining, refining, and transportation of fuels are defined as **precombustion data**. Precombustion data and combustion data together are referred to as **fuel-related data**.

Fuel-related data are developed for fuels that are burned directly in industrial furnaces, boilers, and transport vehicles. Fuel-related data are also developed for the production of electricity. These data are assembled into a database from which the energy requirements and environmental emissions for the production and combustion of process fuels are calculated.

Energy data are developed in the form of units of each primary fuel required per unit of each fuel type. For electricity production, federal government statistical records provided data for the amount of fuel required to produce electricity from each fuel source, and the total amount of electricity generated from petroleum, natural gas, coal, nuclear, hydropower, and other (solar, geothermal, etc.). In this study, the Oregon grid is used to model electricity used for processes taking place in Oregon. Literature sources and federal government statistical records provided data for the emissions resulting from the combustion of fuels in utility boilers, industrial boilers, stationary equipment such as pumps and compressors, and transportation equipment. Because electricity and other fuels are required in order to produce electricity and primary fuels, there is a complex and technically infinite set of interdependent steps involved in fuel modeling. An input-output modeling matrix is used for these calculations.

In 2003, Franklin Associates updated its fuels and energy database for inclusion in the U.S. LCI database. This fuels and energy database, which is published in the U.S. LCI Database, is used in this analysis, although fuel combustion emissions have been updated wherever possible with data from Argonne National Laboratory's GREET model 1.8b, released in May 2008.

Data Quality Goals for This Study

ISO standard 14044:2006 states that "Data quality requirements shall be specified to enable the goal and scope of the LCA to be met." Data quality requirements include time-related coverage, geographical coverage, technology coverage, and more. The data quality goal for this study was to maximize transparency by using life cycle data from credible publicly available sources to the extent possible, and to model all systems to reflect Oregon-specific conditions and practices, where appropriate. Where publicly available life cycle data were not available, processes and materials in this study were modeled based on Franklin Associates' LCI database. The quality of individual data sets vary in terms of age, representativeness, measured values or estimates, etc.; however, all materials and process data sets used in this study were thoroughly reviewed for accuracy and currency and updated to the best of our capabilities for this analysis. The data sources for each unit process are documented in the tables and references in the appendices to this report (a separate document).

One data goal that was not met in this project was the goal of obtaining actual data on water processing and bottling operations from bottling companies. Despite repeated efforts, it was not possible to obtain primary data from the bottlers that were contacted; thus, water processing data were largely estimated from published information, as documented in the appendices.

Another goal that was not met in this report was the goal to evaluate recycling of PLA. No published data could be found at a level of detail that allowed estimation of the unit process requirements for recycling PLA. Furthermore, PLA recycling is not currently a mainstream waste management option. NatureWorks LLC's website states that PLA "has the potential to be recycled once there is a sufficient volume of product in the market and the infrastructure is in place to make recycling economically feasible."[7] A

7 NatureWorks LLC website FAQ section: http://natureworks.custhelp.com/cgi-bin/natureworks.cfg/php/enduser/std_alp.php?p_sid=4xTk3cii&p_accessibility=0. Response to question "Can Ingeo™ [PLA] polymer be recycled?"

July 2006 LCA study commissioned by NatureWorks[8] included PLA recycling as an option and showed environmental benefits for PLA recycling, but the report did not provide sufficient detail on the PLA recycling process to be able to model the process in this analysis.

Data Accuracy

An important issue to consider when using LCI study results is the reliability of the data. In a complex study with literally thousands of numeric entries, the accuracy of the data and how it affects conclusions is truly a complex subject, and one that does not lend itself to standard error analysis techniques. Techniques such as Monte Carlo analysis can be used to study uncertainty, but the greatest challenge is the lack of uncertainty data or probability distributions for key parameters, which are often only available as single point estimates. However, the reliability of the study can be assessed in other ways.

A key question is whether the LCI profiles are accurate and study conclusions are correct. The accuracy of an environmental profile depends on the accuracy of the numbers that are combined to arrive at that conclusion. Because of the many processes required to produce each container or packaging material, many numbers in the LCI are added together for a total numeric result. Each number by itself may contribute little to the total, so the accuracy of each number by itself has a small effect on the overall accuracy of the total. There is no widely accepted analytical method for assessing the accuracy of each number to any degree of confidence. For many chemical processes, the data sets are based on actual plant data reported by plant personnel. The data reported may represent operations for the previous year or may be representative of engineering and/or accounting methods. All data received are evaluated to determine whether or not they are representative of the typical industry practices for that operation or process being evaluated.

There are several other important points with regard to data accuracy. Each number generally contributes a small part to the total value, so a large error in one data point does not necessarily create a problem. For process steps that make a larger than average contribution to the total, special care is taken with the data quality.

There is another dimension to the reliability of the data. Certain numbers do not stand alone, but rather affect several numbers in the system. An example is the amount of material required for a process. This number will affect every step in the production sequence prior to the process. Errors such as this that propagate throughout the system are more significant in steps that are closest to the end of the production sequence. For example, changing the weight of an input to the final fabrication step for a plastic component changes the amounts of resin inputs to that process, and so on back to the quantities of crude oil and natural gas extracted.

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8 **Life Cycle Assessment of Polylactide (PLA): A comparison of foodservice packaging made from NatureWorks® PLA and alternative materials**. IFEU Heidelberg, July 2006. Commissioned by NatureWorks LLC.

In addition to the accuracy of the underlying data sets used to model each unit process, an added dimension to the drinking water analysis is the unlimited possibilities for variations in container weights, recycled content, fabrication energy, transportation distances, consumer use behavior, etc. for the drinking water systems studied. Because of this, the life cycle model was set up as a dynamic model capable of evaluating a wide range of user-defined scenarios. The program TopRank was also used to evaluate the sensitivity of results to variations in individual modeling parameters. These results are presented in Chapter 2.

METHODOLOGY ISSUES

The following sections discuss how several key methodological issues are handled in this study.

Precombustion Energy and Emissions

The energy content of fuels has been adjusted to include the energy requirements for extracting, processing, and transporting fuels, in addition to the primary energy of a fuel resulting from its combustion. In this study, this additional energy is called precombustion energy. Precombustion energy refers to all the energy that must be expended to prepare and deliver the primary fuel. Adjustments for losses during transmission, spills, leaks, exploration, and drilling/mining operations are incorporated into the calculation of precombustion energy.

Precombustion environmental emissions (air, waterborne, and solid waste) are also associated with the acquisition, processing, and transportation of the primary fuel. These precombustion emissions are added to the emissions resulting from the burning of the fuels.

Electricity Grid Fuel Profile

In general, detailed data do not exist on the fuels used to generate the electricity consumed by each industry. Electricity production and distribution systems in the United States are interlinked and are not easily separated. Users of electricity, in general, cannot specify the fuels used to produce their share of the electric power grid.

For most processes in this analysis, electricity generation is modeled based on the United States national average fuel consumption by electrical utilities. For processes that are known to occur in Oregon, the mix of fuels used to generate the electricity used in Oregon is modeled. For container fabrication and filling operations that occur outside the U.S., the appropriate country grid mix is used, based on statistics from the International Energy Agency[9].

9 http://iea.org/Textbase/stats/prodresult.asp?PRODUCT=Electricity/Heat

METHODOLOGICAL DECISIONS

Some general decisions are always necessary to limit a study such as this to a reasonable scope. It is important to understand these decisions. The key assumptions and limitations for this study are discussed in the following sections.

Geographic Scope

Data for foreign processes are generally not available. This is usually only a consideration for the production of oil that is obtained from overseas. In cases such as this, the energy requirements and emissions are assumed to be the same as if the materials originated in the United States. Since foreign standards and regulations vary from those of the United States, it is acknowledged that this assumption may introduce some error. Transportation of crude oil used for petroleum fuels and plastic resins is modeled based on the current mix of domestic and imported crude oil used.

Other processes in this analysis modeled as occurring outside the United States include production of virgin aluminum and steel reusable drinking containers and the processing and bottling of water imported from several countries. Fabrication of the bottles used to package imported water was assumed to occur in the country in which the water was bottled. Recovered PET bottles were assumed to be exported to China for recycling, so PET resin production emissions are based on the U.S. grid, while credits for recycled resin are based on PET production using the Chinese electricity grid. (Recovered metals, glass, and corrugated were assumed to be recycled in the U.S.) For processes occurring outside the U.S., U.S. process energy requirements were used, but production of process electricity was modeled based on that country's electricity grid.

Trip Allocation for Purchases of Bottled Water

Unlike consumption of tap water, which requires no travel on the part of the consumer, and consumption of HOD water, which is delivered by a truck used specifically for this purpose, bottled water is most often picked up by the consumer on an outing that may have several purposes. The consumer is likely to run more than one errand on the same outing, and it is also likely that additional items will be purchased at the same location when the consumer purchases bottled water.

This analysis uses a modeling approach that is based on bottled water being purchased one case at a time, with 24 bottles per case. The number of trips required to purchase 1,000 gallons of water depends on the volume of water in an individual bottle and the number of bottles in the case, both of which can be varied in the model. Each time a trip is made to purchase water, it is assumed that the case of water is purchased on an outing that includes one other errand in addition to the stop where water is purchased. The round-trip distance from the consumer's home to the purchasing location is scaled up to account for the additional distance traveled to include the second stop (home to stop 1, stop 1 to stop 2, and stop 2 back to home). The overall distance traveled is divided by two to allocate half to each stop made.

Furthermore, it is reasonable to assume that any item purchased on a trip to a grocery or other retail store could warrant an individual trip to the store if the item were not purchased together with other items as part of a combined purchase. Therefore, the burdens for making the stop at the store can be allocated over the number of items purchased. For example, if 25 items are purchased on a trip to a store, each item would be allocated 4% of the burdens for making the stop at the store. For purchasing bottled water on a two-errand outing, most modeling scenarios in this analysis use a trip allocation of 4 percent, although one scenario models a two-errand trip in which only water is purchased on the stop at the grocery store, so that 100 percent of the burdens for that stop are allocated to water. The 25-item purchase is an estimate by the LCA practitioner, since no data were readily available for consumer purchasing patterns on an individual shopping trip basis.

In addition to allocating a portion of the total vehicle fuel use to bottled water, the analysis also takes into account the marginal increase in the loaded vehicle weight due to a case of water and the associated slight decrease in fuel economy over the distance the water is transported from store to home. The baseline fuel economy used for the consumer vehicle was 19.9 miles per gallon.[10]

End of Life Management

In Oregon, municipal solid waste (MSW) that is not recovered for recycling or composting is managed 93 percent by weight to landfill (LF), 6 percent to waste-to-energy (WTE) incineration, and 1 percent to facilities that burn material without energy recovery.[11] Thus, the calculations of the GWP (Global Warming Potential) impacts for discarded containers and packaging are based on this management scenario for the postconsumer containers and packaging that are not recovered for recycling or composting.

In this study, estimates of the end results of landfilling and WTE combustion are limited to energy recovery and global warming potential effects. There are GWP contributions from WTE combustion of postconsumer containers and packaging and from fugitive emissions of landfill methane from decomposition of landfilled paperboard (corrugated) packaging, and potentially from decomposition of PLA. There are also GWP credits for grid electricity displaced by the generation of electricity from WTE combustion of postconsumer containers and packaging and from WTE combustion of methane recovered from decomposition of landfilled paperboard packaging, and potentially from decomposition of PLA. Some carbon is also sequestered in the biomass-derived containers and packaging that do not decompose. Because of uncertainties about decomposition of PLA in landfills, the PLA scenarios include separate scenarios for no decomposition and complete decomposition of landfilled PLA bottles.

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10 Average fuel economy for Oregon personal vehicles according to information provided by Oregon DEQ.

11 Information provided by Oregon DEQ in July 2008.

In this study, decomposition of landfilled corrugated packaging is modeled based on the maximum decomposition of corrugated in landfill simulation experiments conducted by Dr. Morton Barlaz, et al.[12] The landfill simulation experiments conducted by Dr. Barlaz analyzed decomposition of office paper, clay-coated magazine paper, newspaper, and corrugated. Because the landfill simulation experiments were designed to maximize decomposition, the estimates presented here should be considered an **upper limit** for landfill gas generation from decomposition of corrugated packaging.

For paper and paperboard materials, the cellulose and hemicellulose fractions of the material decompose to some extent, while the lignin fraction of the material tends to decompose to a much lesser extent under anaerobic conditions. Thus, the potentially degradable carbon content of the landfilled material is based on its cellulose and hemicellulose content. Based on the cellulose, hemicellulose, and lignin percentages in each material, and the carbon content of each fraction, the total carbon content of corrugated is calculated as 43.2 percent (29.9 percent potentially degradable, 13.3 percent in lignin).

In the Barlaz experiments, the following conditions were used to simulate enhanced decomposition (such as might occur in a bioreactor-type landfill or under landfill conditions most favorable to decomposition): addition of a seed of well-decomposed refuse to help initiate decomposition, incubation at about 40°C, and leachate recycling and neutralization. The maximum degree of decomposition for the cellulose and hemicellulose fractions of the corrugated samples was 64 percent for the cellulose and 62 percent for the hemicellulose. The remaining biomass carbon content of the material did not degrade.

The composition of landfill gas as generated is approximately 50 percent by volume methane and 50 percent by volume CO_2. Oregon DEQ estimates that for material currently placed in a landfill, about 38 percent of methane that results from decomposition over time will be released to the environment as methane. Of the remaining 62 percent, 37 percent will be burned with energy recovery, 21 percent flared without energy recovery, and about 4 percent oxidized as it makes its way to the landfill surface.[13] This is similar to U.S. EPA estimates of conversion of landfill methane releases: 25 percent landfill gas combustion with energy recovery, 23 percent flaring, and 5 percent oxidation, with the balance of the methane from decomposition released to the atmosphere.[14]

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12 Barlaz, Morton, et al. "Biodegradability of Municipal Solid Waste Components in Laboratory-Scale Landfills." Published in Environmental Science & Technology. Volume 31, Number 3, 1997.

13 Information provided by Oregon DEQ in July 2008.

14 U.S. EPA. **Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006** (February 2008). Calculated from 2006 data in Table 8-4. Accessible at http://www.epa.gov/climatechange/emissions/usinventoryreport.html.

Biomass CO_2 released from decomposition of paper products or from oxidation of biomass-derived methane to CO_2 is considered carbon neutral, as the CO_2 released represents a return to the environment of the carbon taken up as CO_2 during the plant's growth cycle and does not result in a net increase in atmospheric CO_2. Thus, biomass-derived CO_2 is not included in the GHG results shown in this analysis. Methane releases to the environment from anaerobic decomposition of biomass are *not* considered carbon neutral, however, since these releases resulting from human intervention have a higher global warming potential (GWP) than the CO_2 taken up or released during the natural carbon cycle.

The Barlaz experiments did not test PLA products. There is some uncertainty about the potential for PLA products to decompose in landfills, as the potential is strongly dependent on temperature and humidity. The PLA must first hydrolyze to a low enough molecular weight before biodegradation can begin. NatureWorks LLC's website states that PLA in an inactive landfill (i.e., low temperature, limited moisture) would not become biologically active, although PLA placed in a biologically active landfill would actively biodegrade, contributing to methane production.[15] Temperature and moisture conditions in Oregon landfills may be sufficient to support hydrolysis. Because of the uncertainty surrounding PLA degradation in landfills, the LCI model was set up to evaluate a range of decomposition scenarios for landfilled PLA containers.

When PLA is modeled as decomposing in a landfill, this analysis models the decomposition emissions based on the carbon content of PLA, which is 50 percent by weight, based on the chemical formula of the monomer unit. In the maximum decomposition scenario, all of the carbon in the PLA is modeled as degrading to produce an equimolar mix of carbon dioxide and methane, with the carbon dioxide considered carbon neutral. The fate of the landfill gas is modeled the same as the landfill gas from decomposition of the corrugated.

The U.S. EPA's Landfill Methane Outreach Program (LMOP) Landfill Database[16] indicates that the majority of landfill gas burned with energy recovery is used to produce electricity. The gross energy recovered from combustion of LF gas from each material is converted to displaced quantities of grid electricity using an efficiency factor of 1 kWh generated per 11,700 Btu of LF gas burned.[17] Each container system is credited with avoiding the GWP associated with production of the offset quantity of Oregon grid electricity.

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15 NatureWorks LLC Landfill website: http://www.natureworksllc.com/our-values-and-views/end-of-life/landfill.aspx

16 Operational LFG energy projects spreadsheet, sorted by LFGE utilization type and project type. Accessible at http://www.epa.gov/lmop/proj/#1.

17 LMOP Benefits Calculator. Calculations and References tab. Accessible at http://www.epa.gov/lmop/res/lfge_benefitscalc.xls

For the carbon that remains fixed in the landfilled biomass-derived material (e.g., in the undecomposed portion of the corrugated packaging and PLA containers), a sequestration credit is given for the equivalent pounds of CO_2 that the sequestered carbon could produce. The sequestration credit is based on the carbon content of the material remaining after maximum landfill decomposition has taken place.

Items made of conventional fossil-derived plastic resins do not decompose to produce methane in landfills[18], nor is any carbon sequestration credit assigned to fossil-derived plastics. The U.S. EPA greenhouse gas accounting methodology does not assign a carbon sequestration credit to landfilling of fossil-derived materials because this is considered a transfer between carbon stocks (from oil deposit to landfill) with no net change in the overall amount of carbon stored.[19]

Waste-to-energy combustion of postconsumer material is modeled using a similar approach to the landfill gas combustion credit. However, for WTE combustion of containers and packaging, the CO_2 releases are modeled based on the **total** carbon content of the material oxidizing to CO_2. For combustion of paperboard and PLA, the CO_2 produced is considered carbon-neutral biomass CO_2, while the CO_2 from combustion of fossil-derived resins is fossil CO_2.

The gross heat produced from WTE combustion is calculated based on the pounds of material burned and the higher heating value of the material. The heat is converted to kWh of electricity using a conversion efficiency of 1 kWh per 19,120 Btu for mass burn facilities[20], and a credit is given for avoiding the GWP associated with producing the equivalent amount of Oregon grid electricity.

The net end-of-life GWP for each container system is calculated by summing the individual impacts and credits described above, based on the percentages of Oregon solid waste managed by landfill, waste-to-energy combustion, and combustion without energy recovery.

Limitations of End-of-Life Modeling Approach. As noted, the landfill methane calculations in this analysis are based on the **aggregated** emissions of methane that may result from decomposition of the degradable carbon content of the landfilled material. The long time frame over which those emissions occur has implications that result in additional uncertainties for the landfill methane GWP estimates.

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18 U.S. EPA. **Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks.** Third Edition. September 2006. Page 79 of Chapter 6 Landfilling states "Plastics, carpet, PCs, clay bricks, concrete, fly ash, and tires do not biodegrade measurably in anaerobic conditions, and therefore do not generate any CH4."

19 Ibid. Section 1.3, subsection Carbon Stocks, Carbon Storage, and Carbon Sequestration. Page 6.

20 Ibid. Chapter 5 Combustion, section 5.1.5. Calculation is based on 550 kWh produced per ton of MSW burned, with a heat value of 5,000 Btu per pound of MSW. For mass burn facilities, 523 kWh of electricity are delivered per 550 kWh generated. Full report and individual chapters of the report are accessible at http://www.epa.gov/climatechange/wycd/waste/SWMGHGreport.html.

- In this analysis, the management of the aggregated landfill methane emissions is modeled based on **DEQ's projections of future percentages** of flaring, WTE combustion, and uncaptured releases. These projections are likely conservative in that they do not account for increases in gas recovery efforts resulting from future regulations (such as cap-and-trade) or emissions offset markets. Over time, it is likely that efforts to mitigate global warming will result in increased efforts to capture and combust landfill methane. Combustion of biomass-derived methane converts the carbon back to CO_2, neutralizing the net global warming impact. In addition, if the combustion energy is recovered and used to produce electricity, there would be GWP credits for displacing grid electricity. With increased future capture and combustion of landfill methane, the future net effect of landfill methane would become less negative.
- Although the landfill methane releases occur gradually over many years, the modeling approach used here models the impacts of the aggregated emissions using 100-year global warming potentials. This is consistent with the use of 100-year global warming potentials used for all other life cycle greenhouse gas emissions. Future refinements to end-of-life modeling may include time-scale modeling of landfill methane emissions; however, this is not part of the current study.

System Components Not Included

The following components of each system are not included in this LCI study:

Water Use. There is currently a lack of water use data on a unit process level for life cycle inventories. In addition, water use data that are available from different sources do not use a consistent method of distinguishing between consumptive use and non-consumptive use of water or clearly identifying the water sources used (freshwater versus saltwater, groundwater versus surface water). A recent article in the International Journal of Life Cycle Assessment summarized the status and deficiencies of water use data for LCA, including the statement, "To date, data availability on freshwater use proves to be a limiting factor for establishing meaningful water footprints of products."[21] The article goes on to define the need for a standardized reporting format for water use, taking into account water type and quality as well as spatial and temporal level of detail.

Because of the lack of complete and consistent data on water use for raw material and intermediate unit processes, Franklin Associates' LCI database does not currently include water use. In this analysis, wastewater quantities are estimated only for water treatment processes and container washing operations.

21 Koehler, Annette. "Water use in LCA: managing the planet's freshwater resources." Int J Life Cycle Assess (2008) 13:451-455.

Capital Equipment. The energy and wastes associated with the manufacture and installation of capital equipment and infrastructure are not included. This includes equipment to manufacture buildings, motor vehicles, and industrial machinery, and the installation of water distribution piping. The energy and emissions associated with such capital equipment generally, for 1,000 pounds of materials, become negligible when averaged over the millions of pounds of product manufactured over the useful lifetime of the capital equipment.

Space Conditioning. The fuels and power consumed to heat, cool, and light manufacturing establishments are omitted from the calculations in most cases. For manufacturing plants that carry out thermal processing or otherwise consume large amounts of energy, space conditioning energy is quite low compared to process energy. Energy consumed for space conditioning is usually less than one percent of the total energy consumption for the manufacturing process. This assumption has been checked in the past by Franklin Associates staff using confidential data from manufacturing plants. In this analysis, bottled water purchased in retail stores has not been assigned any share of the store's general space conditioning energy.

Support Personnel Requirements. The energy and wastes associated with research and development, sales, and administrative personnel or related activities have not been included in this study. Similar to space conditioning, energy requirements and related emissions are assumed to be quite small for support personnel activities.

Miscellaneous Materials and Additives. Selected materials such as catalysts, pigments, or other additives which individually account for less than one percent by weight of the net process inputs are typically not included in the assessment unless inventory data for their production are readily available or there is reason to believe that these additives have environmental impacts that are very high in relation to their mass.

In this study, no pigments or other resin additives were included in the analysis, nor did the analysis include printing inks that may be applied to containers, boxes, or labels. Only a small percentage of single-use water bottles are tinted; the overwhelming majority are clear. The project scope and budget did not include collection of primary data on the types and quantities of pigments added to containers or used to print container labels or packaging

Omitting miscellaneous materials and additives helps keep the scope of the study focused and manageable within budget and time constraints. While there are energy and emissions associated with production of materials that are used in very low quantities, the amounts would have to be disproportionately high per pound of material for such small additives to have a significant effect on **overall** life cycle results for the systems studied.

Rebound Effect. The analysis does not include any analysis of the environmental impacts of changes in consumer behavior that may be associated with choosing one water delivery system over another. For example, if consumers choose to drink tap water rather than purchasing bottled water, they may choose to save or invest the money that they do not spend on bottled water, or they may choose to spend the money on a different item or activity. Conversely, if consumers purchase bottled water, this will reduce the money they have available to spend on other items and activities. Alternative purchased items or activities may have environmental impacts that are greater or lesser than the impact of purchasing bottled water. It is beyond the scope of this analysis to make projections about the environmental impacts of alternative uses of consumers' spending dollars that are currently used to purchase bottled water.

CHAPTER 2

LIFE CYCLE INVENTORY RESULTS

INTRODUCTION

A life cycle inventory (LCI) examines the sequence of steps in the life cycle of a product system, beginning with raw material extraction and continuing on through material production, product fabrication, use, reuse or recycling where applicable, and final disposition. For each life cycle step, the inventory identifies and quantifies the material inputs, energy consumption, and environmental emissions (atmospheric emissions, waterborne wastes, and solid wastes). The information from this type of analysis can be used as the basis for further study of the potential improvement of resource use and environmental emissions associated with product systems. It can also pinpoint areas (e.g., material components or processes) where changes would be most beneficial in terms of reduced energy use or environmental emissions.

STUDY GOAL AND INTENDED USE

The LCI results in this chapter are part of a complete life cycle assessment (LCA) of drinking water systems. Some conclusions on metrics such as energy use and solid waste generation can be drawn based on the inventory results, while other observations and conclusions will be based on the results of the life cycle impact assessment (LCIA) in Chapter 3.

The goal of the LCA is to evaluate the environmental implications of various systems for delivery and consumption of drinking water, including bottled water, tap water consumed from reusable containers, and home/office delivery (HOD) water consumed from reusable containers. The analysis includes water processing, production of containers and packaging materials, filling, transport, and end-of-life management of containers and packaging. The analysis also looks at transportation of bottled water imported from several foreign locations.

This study uses container weight and packaging data obtained by weighing purchased samples of various brands of bottled water and reusable drinking containers,[22] and import distances are estimated based on the locations of several countries where popular brands of imported water are bottled. However, the companies producing these brands of bottled water did not participate directly in this study, and their specific operations may be significantly different from the data sets and modeling assumptions used in this report. Thus, **this report should in no way be construed as representing any specific brands of bottled water or reusable containers available in the marketplace.**

[22] Supplemented with information from a published article about bottle weight trends: Bauerlein, Valerie. "Pepsi to Pare Plastic for Bottled Water." Wall Street Journal. March 25, 2009.

The primary intended use of the study results is to inform DEQ about the environmental burdens and tradeoffs associated with various options for providing drinking water to consumers and behavioral choices of consumers. DEQ is also interested in better understanding the environmental burdens and tradeoffs of end-of-life management options (recycling, composting, landfilling, etc.). This analysis contains comparative statements about the results for the drinking water subscenarios analyzed. Because DEQ will make the results of this study, including comparative statements, publicly available, this report is being peer reviewed in accordance with ISO standards for life cycle assessment.[23]

SYSTEMS STUDIED

The following drinking water systems are analyzed in this study:

- Bottled water packaged in and consumed from individual bottles:
  - Virgin PET bottles (16.9 ounce, 8 ounce, and one liter)
  - PET bottles with a mix of virgin and recycled content (16.9 ounce)
  - Virgin PLA bottles (16.9 ounce)
  - Glass bottles with a mix of virgin and recycled content (12 ounce)
- Tap water consumed from reusable containers:
  - Virgin aluminum bottle with plastic closure (20 ounce)
  - Virgin steel bottle with plastic closure (27 ounce)
  - Virgin plastic bottle with plastic closure (32 ounce)
  - Drinking glass with a mix of virgin and recycled content (16 ounce)
- Home/office delivery (HOD) water consumed from reusable containers
  - Virgin polycarbonate bottles
  - Virgin PET bottles
  - Same reusable containers listed under Tap

Detailed descriptions of the drinking water systems are provided in Appendix B of the appendix document accompanying this report; however, to assist in interpretation of the results, a few details about the systems are worth noting here:

- Most individual bottled water scenarios evaluated in this analysis are for a 16.9 oz (500 ml) bottle, which has by far the largest share of the bottled water market; however, 8 oz and 1 liter sizes were also considered in the subscenarios.

23 International Standards Organization. ISO 14040:2006 Environmental management—Life cycle assessment—Principles and framework, ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines.

- The reusable drinking containers evaluated varied in size (volume) and weight; the sizes modeled were based on the sizes of leading brands of aluminum and steel containers available in the marketplace and commonly available sizes of plastic water bottles and drinking glasses.
- Because HOD containers circulate in a closed system, all HOD bottles are modeled as being recycled when removed from service. For individual bottled water sizes and reusable metal drinking containers, variations in recycling rates are evaluated in the subscenarios.
- The processing requirements for tap water and processed municipal drinking water included pumping energy for distribution and were scaled up by 15 percent to cover the estimated loss rate due to leaks occurring within the distribution infrastructure.

In this chapter, detailed LCI results are presented for one example scenario for each drinking water system, and the life cycle stages that make the largest contributions to energy, solid waste, and greenhouse gas emissions are identified. This chapter also includes a sensitivity analysis on the three example scenarios to identify variations that have the greatest effect on results for each type of drinking water system.

To assist in selection of the subscenarios for analysis, the first draft LCI included contribution analysis for several potential scenarios for each drinking water system. The results figures and accompanying discussion from the draft LCI are attached to this report as Appendix 1. Several of the scenarios in the appendix are the same as or similar to subscenarios modeled in this chapter; however, the results in the appendix may not exactly match the results in the report due to some adjustments that were made to the LCI model after the draft.

Based on the results of the contribution analyses and sensitivity analyses, a set of 48 subscenarios were selected for analysis. Comparative inventory results for energy and solid waste for the 48 subscenarios are presented in the tables and figures in this chapter. Impact assessment results for the 48 subscenarios are presented in Chapter 3.

The following table summarizes the model settings used for the three example scenarios for which results are described in detail in the first part of this chapter. For each drinking water system, the example scenario represents only one of the many combinations of parameters that can be modeled for each of the drinking water systems and is not meant to be interpreted as the most likely or most representative scenario for that system. Parameters that are modeled consistently for all systems (e.g., wastewater treatment) are not shown in the table.

Table 2-1. Modeling Parameters for Example Drinking Water Systems

	Bottled Water	Tap/Reusable	HOD/Reusable
Bottle material	PET	Reusable virgin aluminum drinking container made in Switzerland	Reusable virgin aluminum drinking container made in Switzerland
Container capacity	16.9 oz	20 oz	20 oz
Container weight	13.3 g	100 g	100 g
Recycled content	0%	0%	0%
Times filled per day		1	1
Years use before disposal or recycling		1	1
Days use of reusable drinking container before washing in home dishwasher		1	1
Reusable container washing in home dishwasher with high or low water use		high water use	high water use
HOD container material			Polycarbonate
HOD container weight			750 g
Lifetime uses			40
Water in bottle	OR purified municipal water with reverse osmosis, ozone treatment, and UV	Oregon tap water (municipal water with no additional purification steps)	OR purified municipal water with reverse osmosis, ozone treatment, and UV
Transport of empty single-serve water bottle from off-site molder to filler	0 miles (molded at filling location)		
Single-serve bottles rinsed before filling	no		
Distance from filler to store	50 mi		
Distance from store to home	5 mi		
Personal vehicle fuel usage allocated to purchased water	4% (e.g., 1 of 25 items purchased)		
Miles on HOD distribution route			75 miles
Chilling	none	none	HOD chiller unit
Container recycling (methodology 1)	62%	0%	0% recycling of aluminum bottle, 100% recycling of HOD container
Recycling of corrugated packaging	76%		

SCOPE AND BOUNDARIES

The LCI includes all steps in the production of each drinking water container system, from extraction of raw materials through production of the materials used in the containers, fabrication of finished containers and closures, and transport to filling locations. Treatment of municipal drinking water and additional processing steps used to purify bottled municipal water and natural water such as spring water are included in the analysis. Bottle filling and washing operations are included, as is production of secondary packaging used for shipment of filled containers, distribution of filled containers, washing of reusable containers, and end-of-life management of containers and associated packaging components. Various options for chilling water are also included in the model.

All washing of reusable personal drinking containers in this study is modeled based on use of a residential dishwasher, which is expected to be the most common method used by consumers for washing of these containers. Containers may also be hand-washed; however, water and detergent use for hand washing can vary widely based on the practices of individual consumers. As a result, hand washing of containers can be either more or less burdensome than machine washing.

The scope of the study did not include analysis of scenarios for HOD and tap water consumed from disposable cups, nor did the study include any scenarios in which disposable drinking water bottles sold filled with water were refilled by consumers and used as a reusable drinking container. Additional at-home purification of tap water, such as use of tap water filters, was not included in the scope of the analysis. The scope of the analysis did not include greenhouse gas effects of direct and indirect land use changes that may be associated with corn growing for PLA production.

In Oregon, municipal solid waste (MSW) that is not recovered for recycling or composting is managed 93 percent by weight to landfill (LF), 6 percent by weight to waste-to-energy (WTE) combustion, and 1 percent by combustion without energy recovery, as documented in Appendix J. An energy credit is given for material that is managed by WTE combustion, based on the amount of each material burned, its heating value, and the efficiency of converting the gross heat of combustion to useful energy.

The end-of-life emissions results take into account the effects of combustion, decomposition, and energy recovery, including estimates of release of carbon dioxide from combustion of materials and methane from decomposition of degradable landfilled material, emission credits for avoided grid electricity displaced by electricity generated from WTE operation and from landfill gas combustion, and carbon sequestration in landfilled biomass-derived material that does not decompose. The end-of-life modeling and recycling methodologies are described in Chapter 1.

FUNCTIONAL UNIT

In a life cycle study, systems are evaluated on the basis of providing a defined function (called the **functional unit**). The function of each system analyzed in this report is to deliver drinking water to consumers. The functional unit selected for this analysis is delivering 1,000 gallons of drinking water to a consumer, including use of a bottle or reusable drinking container, and end-of-life management of the containers and packaging.

The functional equivalence is based on delivering drinking water that meets water quality standards set by the Food and Drug Administration (FDA), EPA, and state governments. The scope of the analysis does not include evaluating other differences in the quality of the water (e.g., taste, fluoride or mineral content, etc.) or temperature of the water, or any potential health impacts that may be associated with the use of specific container materials. Each subscenario evaluated clearly indicates whether the results included chilling of the water, and if so, the chilling method used. No carbonated waters were evaluated.

The functional unit was based on 1,000 gallons of delivered water for several reasons:

1. This basis produces results of a sufficient magnitude to be shown as whole numbers in the results tables and figures. Using a smaller unit, such as a liter of water, would produce results of a very small magnitude that would need to be shown in scientific notation.
2. It is easier to understand reuse rates for 5-gallon HOD bottles when the functional unit is a multiple of the container volume (e.g., 1,000 gallons = 200 HOD bottle trips).
3. Bottled water is typically packaged and purchased in multi-container cases, so again it makes sense to use a basis that is a multiple of the functional unit (1,000 gallons = 315 cases of 24 16.9 oz bottles) rather than a fraction of a purchasing unit (1 liter = two 16.9 oz bottles, equivalent to 1/12 of a case, or 0.083 cases).

Results shown on the basis of 1,000 gallons can easily be converted to any desired volume basis. For example, to convert results per 1,000 gallons to result per liter, first divide the 1,000 gallon results by 1,000 (to arrive at results on a per gallon basis), then divide the per gallon results by 3.8 liters per gallon to arrive at per liter results.

DATA SOURCES

The report appendices (a separate document) provide detailed description and documentation of the data used in the LCI models:

- Appendix A: Extraction, processing, and combustion of process and transportation fuels and electricity
- Appendix B: Weights and material composition of systems studied
- Appendix C: Production of materials used in containers and packaging
- Appendix D: Fabrication of containers and packaging
- Appendix E: Drinking water treatment
- Appendix F: Water bottling operations
- Appendix G: Bottled water distribution
- Appendix H: Drinking water cooling options
- Appendix I: Container washing
- Appendix J: End of life management (including landfilling, combustion, recycling, composting, and wastewater treatment)

This analysis used Oregon-specific data and assumptions for the following:

- Mix of fuels to produce electricity used for processes that occur in Oregon (e.g., processing and filling operations for bottled water processed in Oregon; operation of pumps to deliver municipal tap water to Oregon homes or to pump well water; molding of plastic water bottles produced in Oregon; operation of home dishwashers used to clean reusable containers between uses, HOD container washing operations for HOD bottles that are filled and circulated in Oregon.
- Transportation distances for bottled water
- Mix of residential water from wells and municipal treatment
- Recycling rates for PET bottles, glass bottles, and corrugated packaging
- Percentages of landfilling, waste-to-energy combustion, and combustion without energy recovery for municipal solid waste management of containers that are not recycled
- Modes and distances for transport of postconsumer solid waste to landfill and combustion facilities
- Management of landfill gas

CONTRIBUTION ANALYSIS FOR LCI RESULTS

The presentation and discussion of results in this chapter focuses on energy and solid waste results. Emissions inventory results are not discussed in detail in this chapter. The full emissions inventories serve as inputs for the life cycle impact assessment (LCIA) results presented in Chapter 3.

In each table, the results are broken out into the following categories:

- **Drinking container production –** includes all steps from raw material extraction through fabrication of the container from which the drinking water is consumed (disposable bottle or reusable drinking container) and transport to filling location. For containers with recycled content, the container production burdens reflect the share of virgin material burdens allocated to the container for the recycling methodology chosen. For reusable containers, the manufacturing requirements per container are adjusted to account for the lifetime uses of the container.
- **HOD container production –** includes all process and transportation steps from raw material extraction through fabrication of the finished container, and transport from molder to filler. Manufacturing requirements per container are adjusted for the lifetime uses of the container.
- **Production of caps and closures –** includes all process and transportation steps from raw material extraction through fabrication of caps and closures used on disposable bottles, reusable drinking containers, and HOD bottles, and transport of caps and closures to bottling locations.
- **Production of secondary packaging –** includes all process and transportation steps from raw material extraction through fabrication of corrugated packaging and polyethylene film used as packaging for cases of bottled water, and transport of packaging materials to bottling facilities.

- **Water processing** – energy requirements and emissions for treatment of drinking water. Includes production of treatment chemicals, energy requirements for processing and pumping of municipal tap water, well water, natural water, and purified municipal water for the specified treatment processes (may include reverse osmosis, ozone treatment, and ultraviolet disinfection). Pumping requirements include pumping for processing and distribution.
- **Filling** – requirements for filling containers with drinking water.
- **Distribution of filled containers** – requirements for transport of cases of bottled water to stores or filled HOD containers to point of consumption.
- **Consumer transport** – burdens incurred by the consumer in driving to/from a retail location to purchase bottled water.
- **Home washing of reusable containers** – requirements for cleaning reusable containers between uses, using a residential automatic dishwasher (treatment of water used in the dishwasher is included in the water processing category described above, and treatment of dishwasher effluent water is included in the wastewater treatment category described below). Manufacturing of home dishwasher detergent is not included.[24]
- **Industrial washing of HOD containers** – requirements for commercial washing of HOD containers between uses, including production of cleaning chemicals.
- **Wastewater treatment** – requirements for processing effluent from washing operations or unconsumed drinking water.
- **Chilling** – requirements for chilling drinking water prior to consumption. For bottled water, home refrigeration is evaluated as a chilling option. For tap water, chilling options include home refrigeration or use of ice, and for the HOD system, chilling is done using a chiller base unit on which the bottle is placed.
- **End-of-life management of water bottles, reusable drinking containers, and HOD bottles** – includes requirements for the recycling or composting of each type of container as specified in the model, with the remainder of the material managed by the Oregon-specific percentages of municipal solid waste managed by landfilling, combustion with energy recovery, and combustion without energy recovery. Includes emissions from combustion of material and credits for energy recovered from waste-to-energy combustion of material. For landfilled PLA containers, this category also includes credits for energy recovered from waste-to-energy combustion of landfill gas (for the scenario in which landfill decomposition of PLA is modeled) as well as carbon sequestration credit for carbon content of landfilled PLA that does not decompose.

[24] The decision to exclude detergent manufacture was made during the scoping phase, based on a previous study that indicated that energy requirements for detergent manufacture were small in comparison to the energy requirements for water heating for washing operations.

- **End-of-life management of caps and closures –** end-of-life management by the Oregon-specific percentages of landfilling, combustion with energy recovery, and combustion without energy recovery. Includes emissions from combustion of material and credits for energy recovered from waste-to-energy combustion of material.
- **End-of-life management of secondary packaging –** end-of-life management of corrugated and polyethylene film packaging based on Oregon recycling rate and Oregon-specific percentages of landfilling and combustion with and without energy recovery. Includes emissions from combustion of material and credits for energy recovered from waste-to-energy combustion of material. For landfilled corrugated, also includes credits for energy recovered from waste-to-energy combustion of landfill gas from decomposition of landfilled corrugated and carbon sequestration credit for carbon content of landfilled corrugated that does not decompose.
- **Credits for postconsumer recycling –** credits for the reduction in production and disposal of virgin material allocated to the bottle system as a result of recycling of containers and packaging materials, based on the allocation methodology selected in the model.

Energy Results

Energy by Category. Table 2-2 shows energy results for the three example drinking water scenarios. The results are presented by life cycle stage, and the results for each stage are classified into three categories:

- **Process energy** includes energy for all processes required to produce containers, closures, and packaging, from acquisition of raw materials through manufacture of finished items, as well as energy for water treatment processes, container filling and washing, and operation of equipment used in landfilling postconsumer containers and packaging. For municipal tap water, distribution pumping energy is included in the process energy requirements since it was not possible to separate water treatment energy requirements from energy requirements for water distribution.
- **Transportation energy** is the energy used to move material from location to location during its journey from raw material to finished product, as well as transportation of packaging components to filling locations, distribution of filled containers, consumer trips for purchases of bottled water, and collection and transport of postconsumer material to recyclers, composting facilities, landfills, and combustion facilities.

- **Energy of material resource (EMR)** is not an expended energy but the energy value of fuel resources withdrawn from the planet's finite fossil reserves and used as material inputs for materials such as plastic resins. Use of fossil fuel resources as a material input removes fuel resources from the energy pool; however, some of this energy remains embodied in the plastic material produced. As described in the Methodology Chapter, energy of material resource is a reporting convention applied only to resources that would otherwise be used as fuels; thus, no energy of material resource is reported for biomass-derived materials such as corn inputs to PLA or wood inputs to paperboard production.

Table 2-2 shows that total energy requirements for the example PET bottled water system are dominated by production of the bottles, although the 62 percent recycling rate modeled for the postconsumer bottles provides a significant energy credit. The 62 percent recycling rate is based on the recovery rate of PET soft drink bottles under the Oregon bottle bill; a similar recovery rate is expected for PET water bottles, which were included in the bottle bill as of January 2009. Nearly half of the energy for PET bottle production is energy of material resource for the fossil fuels used as material feedstocks for the bottle resin. Transportation energy accounts for 13 percent of the total life cycle energy requirements, with the majority used for transportation of filled bottles, even though the bottles are filled in state.

For the tap water system with a reusable aluminum bottle, process energy accounts for 97 percent of the life cycle energy requirements. Energy for washing the aluminum container after each use (i.e., one container washing after each 20 ounces of water consumed) accounts for the majority of the energy.

Table 2-2. Energy by Category for Example Drinking Water Systems (million Btu per 1,000 gallons)

	Process	Transport	Energy of Material Resource (EMR)	NET
Example Bottled Water Scenario				
Production of PET bottle	4.08	0.24	3.64	7.96
Production of caps, closures	0.46	0.031	0.63	1.12
Production of secondary packaging	0.67	0.042	0.57	1.28
Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
Filling	0.022	0	0	0.022
Distribution of filled containers (50 mi)	0	0.36	0	0.36
Consumer transport (4% allocated to water)	0	0.47	0	0.47
Wastewater treatment	0.0019	1.6E-06	0	0.0019
Chilling (none)	0	0	0	0
End of life management - bottles @ 62% recycling	0.17	0.20	0	0.37
End of life management - caps & closures	-0.010	0.0088	0	-0.0011
End of life management - secondary packaging	-0.026	0.012	0	-0.014
Credit for recycling (method 1)	-1.08	-0.051	-1.13	-2.25
TOTAL	**4.88**	**1.31**	**3.71**	**9.90**
Percent by category	49%	13%	37%	100%
Example Tap Water Scenario				
Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
Production of HOD bottle	0	0	0	0
Production of caps, closures	0.0083	5.6E-04	0.011	0.020
Water processing (tap)	0.028	1.2E-05	2.8E-05	0.028
Home washing of reusable drinking container (daily, high water use)	1.85	0	0	1.85
Wastewater treatment	0.0062	5.3E-06	0	0.0062
Chilling (none)	0	0	0	0
End of life management - drinking containers @ 0% recycling	4.3E-04	9.1E-04	0	0.0013
End of life management - caps & closures	-1.8E-04	1.6E-04	0	-2.0E-05
Credit for recycling (method 1)	0	0	0	0
TOTAL	**2.18**	**0.029**	**0.048**	**2.25**
Percent by category	97%	1%	2%	100%
Example HOD Water Scenario				
Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
Production of HOD bottle (Polycarb, 40 uses)	0.37	0.0096	0.13	0.51
Production of caps, closures	0.14	0.0076	0.16	0.30
Water processing (purified municipal)	0.60	1.7E-05	4.0E-05	0.60
Filling (reusable drinking container filled once daily)	0.022	0	0	0.022
Distribution of filled containers (50 mi dist, 75 mi route)	0	1.52	0	1.52
Home washing of reusable drinking container (daily, high water use)	1.85	0	0	1.85
Industrial washing of HOD container	0.14	3.6E-05	0	0.14
Wastewater treatment	0.0086	7.3E-06	0	0.0086
Chilling (HOD chiller unit)	2.00	0	0	2.00
End of life management - HOD 100% recycling, container 0%	0.011	0.0023	0	0.014
End of life management - caps & closures	-0.0025	0.0022	0	-2.7E-04
Credit for recycling (method 1)	-0.14	-0.0031	-0.065	-0.21
TOTAL	**5.27**	**1.57**	**0.26**	**7.10**
Percent by category	74%	22%	4%	100%

Energy requirements for the HOD system used together with a reusable aluminum bottle are mainly process energy (74 percent), dominated by energy for washing the aluminum containers between fillings and operation of the chilling unit on the HOD dispenser. Transportation accounts for 22 percent of life cycle energy for the HOD system, primarily for distribution of filled containers.

Although none of the container closures are modeled as being recycled, there are small end-of-life credits shown for caps and closures for each system. This is from the energy recovered from caps that are disposed by WTE combustion. The recovered energy is modeled as displacing an equivalent amount of Oregon grid electricity. The end-of-life credits for secondary packaging include WTE energy from combustion of packaging materials as well as credits for some energy recovery from WTE combustion of landfill gas produced by decomposition of corrugated that is not recycled. Energy credits for recycling of corrugated are included together with credits for container recycling in the credit for recycling line.

Total energy results for the example systems are shown in Table 2-3 broken out by life cycle stage and fuel. Uses of the fossil fuels petroleum, natural gas, and coal include use as direct process fuels, as fuels used to generate electricity, as transportation fuels, and as material feedstocks for the production of plastic resins in this analysis. For drinking water systems utilizing corrugated packaging, the wood energy category includes energy derived from burning wood wastes and black liquor on-site at the pulp mill. The remaining fuels are used for electricity production.

Table 2-3. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

	Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Coproduct	NET
Example Bottled Water Scenario										
Production of PET bottle	3.12	3.27	1.21	0.22	0.16	0	0.088	8.06	0.10	7.96
Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.5E-04	0	6.7E-04	0.36	0	0.36
Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
Chilling (none)	0	0	0	0	0	0	0	0	0	0
End of life management - bottles @ 62% recycling	0.045	0.21	0.094	-0.0024	0.026	0	0.0057	0.37	0	0.37
End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
Credit for recycling (method 1)	-0.88	-0.99	-0.34	-0.018	-0.0093	-0.049	-0.0017	-2.28	-0.032	-2.25
TOTAL	**3.91**	**3.72**	**1.67**	**0.32**	**0.26**	**0.079**	**0.14**	**10.1**	**0.20**	**9.90**
Percent by fuel	39%	37%	17%	3%	3%	1%	1%	100%	0%	0%
Example Tap Water Scenario										
Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
Production of caps, closures	0.013	0.0044	0.0032	1.4E-04	7.6E-04	0	2.1E-04	0.022	0.0015	0.020
Water processing (tap)	0.0052	5.4E-04	0.015	0.0050	7.5E-04	0	0.0013	0.028	0	0.028
Home washing of reusable drinking container (daily, high water use)	0.56	0.029	0.85	0.29	0.040	0	0.077	1.85	0	1.85
Wastewater treatment	0.0011	1.7E-04	0.0035	0.0011	1.5E-04	0	2.8E-04	0.0062	0	0.0062
Chilling (none)	0	0	0	0	0	0	0	0	0	0
End of life management - drinking containers @ 0% recycling	6.1E-05	0.0012	2.7E-05	9.3E-06	1.3E-06	0	2.5E-06	0.0013	0	0.0013
End of life management - caps & closures	-2.5E-05	1.8E-04	-1.2E-04	-4.0E-05	-5.5E-06	0	-1.1E-05	-2.0E-05	0	-2.0E-05
Credit for recycling (method 1)	0	0	0	0	0	0	0	0	0	0
TOTAL	**0.65**	**0.12**	**0.98**	**0.36**	**0.066**	**0**	**0.085**	**2.25**	**0.0015**	**2.25**
Percent by fuel	29%	5%	43%	16%	3%	0%	4%	100%	0%	0%
Example HOD Water Scenario										
Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
Production of HOD bottle (Polycarb, 40 uses)	0.28	0.096	0.11	0.0033	0.018	0	0.0051	0.51	0	0.51
Production of caps, closures	0.21	0.049	0.045	0.0019	0.010	0	0.0030	0.32	0.014	0.30
Water processing (purified municipal)	0.094	0.011	0.33	0.11	0.016	0	0.030	0.60	0	0.60
Filling (reusable drinking container filled once daily)	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
Distribution of filled containers (50 mi dist, 75 mi route)	0.067	1.41	0.031	0.011	0.0015	0	0.0028	1.52	0	1.52
Home washing of reusable drinking container (daily, high water use)	0.56	0.029	0.85	0.29	0.040	0	0.077	1.85	0	1.85
Industrial washing of HOD container	0.024	0.0033	0.075	0.023	0.0053	0	0.0066	0.14	0	0.14
Wastewater treatment	0.0015	2.4E-04	0.0048	0.0015	2.1E-04	0	3.9E-04	0.0086	0	0.0086
Chilling (HOD chiller unit)	0.31	0.037	1.11	0.38	0.053	0	0.10	2.00	0	2.00
End of life management - HOD 100% recycling, container 0%	0.0023	0.0035	0.0058	-2.1E-05	0.0015	0	3.6E-04	0.014	0	0.014
End of life management - caps & closures	-3.5E-04	0.0025	-0.0016	-5.5E-04	-7.6E-05	0	-1.5E-04	-2.7E-04	0	-2.7E-04
Credit for recycling (method 1)	-0.13	-0.044	-0.030	-6.3E-04	-0.0035	0	-9.9E-04	-0.21	0	-0.21
TOTAL	**1.50**	**1.68**	**2.65**	**0.89**	**0.17**	**0**	**0.23**	**7.12**	**0.014**	**7.10**
Percent by fuel	21%	24%	37%	13%	2%	0%	3%	100%	0%	0%

The energy requirements shown in Table 2-3 reflect the withdrawals from the energy pool for each drinking water system. However, not all of this energy is actually expended. Some of the EMR value remains in fossil-derived plastic containers, caps, and water bottle packaging film that goes to landfill. Some processes in the production of plastic resins produce excess energy that is treated as a coproduct. The coproduct energy is shown separately in the column “Energy Coproduct” in Table 2-3.

Energy recovered from WTE combustion of postconsumer containers, closures, and packaging and from combustion of landfill gas is included in the End-of-Life results shown in the table. The credits line reflects the reductions in energy due to recovery and recycling of containers and corrugated packaging at end of life. The net life cycle energy requirements for each system are shown in the last column of Table 2-3.

Fossil fuels account for the majority of energy use (over 75 percent of the total) for each system, although the profiles are different for each drinking water system. Natural gas and petroleum account for a larger percentage of fuel use for the bottled water system than for the other systems, due to the use of these resources not only as process and transportation fuels but also as material feedstocks for the production of the plastic resin in the bottles. Coal and natural gas dominate fossil fuel for the tap water system, mainly due to the use of electricity for dishwasher operation and electricity and natural gas use for heating the water used to wash the containers. Petroleum is only a small percentage of total energy use for the tap water system since this system does not require the use of vehicles to get the water to consumers. The HOD system has significant percentages of energy from natural gas, petroleum, and coal. Coal use is attributed to the electricity used for operating the chiller unit and washing the HOD containers and reusable containers between fillings, while most of the natural gas is used for water heating for the washing operations. Most of the petroleum use is by the trucks making the route deliveries of HOD bottles to customers.

Solid Waste Results

Solid waste results are presented in Table 2-4 using the following three categories:

- **Process wastes** are the solid wastes generated by the various processes from raw material acquisition through fabrication of containers and packaging and water treatment processes.
- **Fuel-related wastes** are the wastes from the production and combustion of fuels used for process energy and transportation energy.
- **Postconsumer wastes** are the containers and packaging components that are landfilled at end of life (after adjustment for any recycling or composting). For materials disposed by combustion, the resulting amount of ash is reported.

Table 2-4. Weight of Solid Waste for Drinking Water Scenarios
(pounds per 1,000 gallons)

	Process Solid Waste	Fuel Solid Waste	Landfilled Post-consumer Waste	Combusted Post-consumer Waste	TOTAL LB SW
Example Bottled Water Scenario					
Production of PET bottle	7.92	41.7	0	0	49.6
Production of caps, closures	1.23	6.07	0	0	7.30
Production of secondary packaging	3.32	7.56	0	0	10.9
Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
Filling	0	0.40	0	0	0.40
Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
Wastewater treatment	0	0.034	0	0	0.034
Chilling (none)	0	0	0	0	0
End of life management - bottles @ 62% recycling	6.88	3.45	142	0	153
End of life management - caps & closures	0	-0.19	24.8	0	24.7
End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
Credit for recycling (method 1)	-0.98	-11.8	0	0	-12.7
TOTAL	**18.4**	**59.2**	**208**	**0.073**	**286**
Percent by category	6.4%	20.7%	72.9%	0.0%	100.0%
Example Tap Water Scenario					
Production of reusable drinking container (20 oz alum, 1 yr use)	11.6	3.43	0	0	15.0
Production of caps, closures	0.022	0.11	0	0	0.13
Water processing (tap)	2.6E-04	0.48	0	0	0.48
Home washing of reusable drinking container (daily, high water use)	0	27.7	0	0	27.7
Wastewater treatment	0	0.11	0	0	0.11
Chilling (none)	0	0	0	0	0
End of life management - drinking containers @ 0% recycling	0	0.0032	3.59	0.27	3.87
End of life management - caps & closures	0	-0.0034	0.45	0	0.45
Credit for recycling (method 1)	0	0	0	0	0
TOTAL	**11.6**	**31.9**	**4.04**	**0.27**	**47.8**
Percent by category	24.3%	66.6%	8.5%	0.6%	100.0%
Example HOD Water Scenario					
Production of reusable drinking container (20 oz alum, 1 yr use)	11.6	3.43	0	0	15.0
Production of HOD bottle (Polycarb, 40 uses)	0.28	3.63	0	0	3.91
Production of caps, closures	0.19	1.53	0	0	1.72
Water processing (purified municipal)	3.7E-04	10.6	0	0	10.6
Filling (reusable drinking container filled once daily)	0	0.40	0	0	0.40
Distribution of filled containers (50 mi dist, 75 mi route)	0	3.70	0	0	3.70
Home washing of reusable drinking container (daily, high water use)	0	27.7	0	0	27.7
Industrial washing of HOD container	4.7E-04	2.43	0	0	2.43
Wastewater treatment	0	0.15	0	0	0.15
Chilling (HOD chiller unit)	0	35.7	0	0	35.7
End of life management - HOD 100% recycling, container 0%	0	0.20	7.43	0.27	7.90
End of life management - caps & closures	0	-0.047	6.18	0	6.14
Credit for recycling (method 1)	-0.11	-1.04	0	0	-1.15
TOTAL	**12.0**	**88.5**	**13.6**	**0.27**	**114**
Percent by category	10.5%	77.4%	11.9%	0.2%	100.0%

As with energy results, the different systems have different solid waste profiles. Solid waste for the PET bottle system is dominated by disposal of postconsumer containers, lids, and packaging. There is also a substantial amount of fuel-related solid waste, mainly from energy use for container production.

The tap water system is the least material-intensive system, and thus the solid waste results are dominated by the fuel-related wastes for container washing. The weight of solid waste from disposal of the reusable containers is about the same as the amount of fuel-related waste required to produce the containers. The life cycle stage with the highest process wastes is production of the reusable container, mainly from the ore processing wastes from virgin aluminum production.

The HOD system results are also dominated by fuel-related wastes, largely those associated with energy use for container washing and water chilling. Disposal of postconsumer containers and lids accounts for about 12 percent of the total weight of solid waste.

Table 2-5 shows the solid weight waste results converted to a volume basis, using landfill densities that take into account not only the density of the material as put into the landfill but also the degree to which the material compacts in the landfill. Because the volume of postconsumer combustion ash is so low, it is included in the total volume of postconsumer weight in Table 2-5 rather than shown separately. Because the fabricated containers and lids compact less densely in the landfill compared to industrial solid wastes (process and fuel-related wastes), postconsumer waste accounts for a higher percentage of the total volume of solid waste compared to its percentage of total weight of solid waste for each system.

Table 2-5. Volume of Compacted Solid Waste for Drinking Water Scenarios (cubic feet per 1,000 gallons)

	Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste*	TOTAL CU FT SW
Example Bottled Water Scenario				
Production of PET bottle	0.16	0.83	0	0.99
Production of caps, closures	0.025	0.12	0	0.15
Production of secondary packaging	0.066	0.15	0	0.22
Water processing (purified municipal)	4.8E-06	0.21	0	0.21
Filling	0	0.0080	0	0.0080
Distribution of filled containers (50 mi)	0	0.017	0	0.017
Consumer transport (4% allocated to water)	0	0.022	0	0.022
Wastewater treatment	0	6.8E-04	0	6.8E-04
Chilling (none)	0	0	0	0
End of life management - bottles @ 62% recycling	0.14	0.069	10.8	11.0
End of life management - caps & closures	0	-0.0038	1.89	1.89
End of life management - secondary packaging	0	-0.0092	1.52	1.51
Credit for recycling (method 1)	-0.020	-0.24	0	-0.25
TOTAL	**0.37**	**1.18**	**14.2**	**15.8**
Percent by category	2.3%	7.5%	90.2%	100.0%
Example Tap Water Scenario				
Production of reusable drinking container (20 oz alum, 1 yr use)	0.23	0.069	0	0.30
Production of caps, closures	4.5E-04	0.0022	0	0.0026
Water processing (tap)	5.2E-06	0.0096	0	0.0096
Home washing of reusable drinking container (daily, high water use)	0	0.55	0	0.55
Wastewater treatment	0	0.0022	0	0.0022
Chilling (none)	0	0	0	0
End of life management - drinking containers @ 0% recycling	0	6.5E-05	0.39	0.39
End of life management - caps & closures	0	-6.8E-05	0.034	0.034
Credit for recycling (method 1)	0	0	0	0
TOTAL	**0.23**	**0.64**	**0.43**	**1.30**
Percent by category	17.9%	49.1%	32.9%	100.0%
Example HOD Water Scenario				
Production of reusable drinking container (20 oz alum, 1 yr use)	0.23	0.069	0	0.30
Production of HOD bottle (Polycarb, 40 uses)	0.0056	0.073	0	0.078
Production of caps, closures	0.0037	0.031	0	0.034
Water processing (purified municipal)	7.3E-06	0.21	0	0.21
Filling (reusable drinking container filled once daily)	0	0.0080	0	0.0080
Distribution of filled containers (50 mi dist, 75 mi route)	0	0.074	0	0.074
Home washing of reusable drinking container (daily, high water use)	0	0.55	0	0.55
Industrial washing of HOD container	9.4E-06	0.049	0	0.049
Wastewater treatment	0	0.0031	0	0.0031
Chilling (HOD chiller unit)	0	0.71	0	0.71
End of life management - HOD 100% recycling, container 0%	0	0.0039	0.69	0.69
End of life management - caps & closures	0	-9.4E-04	0.47	0.47
Credit for recycling (method 1)	-0.0022	-0.021	0	-0.023
TOTAL	**0.24**	**1.77**	**1.16**	**3.17**
Percent by category	7.6%	55.9%	36.5%	100.0%

* Includes volume of postconsumer material that is sent directly to landfills, as well as the volume of ash landfilled after combustion of material that is burned with or without energy recovery.

SENSITIVITY ANALYSIS

The tables and discussion in the preceding section focus on the contribution of life cycle stages to overall results based on an example set of **point values** of modeling parameters for each system. The program TopRank was used to evaluate the sensitivity of results to **ranges** of variations in individual modeling parameters. The following tables identify the parameter variations that cause the largest changes in energy, solid waste, and greenhouse gas results for the example systems.

While global warming potential (GWP) is an impact category rather than an inventory flow, it is included in the sensitivity analysis because of the high level of interest in global warming, which makes GWP an important metric to consider when selecting the 48 drinking water scenarios for analysis in the LCI and LCIA.

The GWP includes greenhouse gas emissions released from the production and combustion of fuels that are used for process and transportation energy, as well as the greenhouse gas emissions that are released directly from processes (e.g., from chemical reactions or decomposition of landfilled material). Results shown in Tables 2-6 through 2-8 are limited to emissions of carbon dioxide, methane, and nitrous oxide. These three atmospheric emissions typically are responsible for over 99 percent of the total global warming potential for most product systems. (The global warming potential results shown in Chapter 3 include GWP for the full set of greenhouse gas emissions.)

Each greenhouse gas has a global warming potential (GWP) that represents the relative global warming contribution of a pound of that particular greenhouse gas compared to a pound of carbon dioxide. The weight of each greenhouse gas from each drinking water system is multiplied by its GWP, then the GWPs for each greenhouse gas are added to arrive at a total GWP (expressed in pounds of CO_2 equivalents) for each system. The GWP calculations in Tables 2-6 through 2-8 use 100-year GWP factors published in the International Panel on Climate Change (IPCC) Second Assessment Report (SAR), published in 1996. The GWP results in Chapter 3 are calculated using the GWP factors in the TRACI LCIA methodology, shown in Table 3-11.

Interpreting the Tables

The column "Reference Value" shows the basic set of parameters used for each example system. For example, the highlighted cells in Table 2-6 shows that the total energy requirements for the example PET bottle system with the defined reference settings are 9.90 million Btu. Total weight of solid waste is 286 pounds, and total global warming potential is 1,121 pounds of CO_2 equivalents.

Each parameter is varied separately while all others are held constant, and the resulting variations in model outputs are tabulated. The Minimum and Maximum columns show the high and low output values that result from the range of input values used for that parameter. The parameters are listed in order of the magnitude of the effect on results. For example, the top line in the Energy section shows that the variations in PET recycling rate resulted in the greatest range in total energy results. The reference setting used for the PET container recycling rate was 62%, and the model was run varying the recycling rate from 0% to 100%, holding all other parameters at their reference setting. Using recycling methodology 1 (open-loop recycling), changing the PET bottle recycling rate from 62% to 100% (with all other parameters held constant) reduced the total energy from 9.90 to 9.21 MMBtu, while reducing the recycling rate to 0% increased the energy total from 9.90 to 12.0 MMBtu.

Varying the PET bottle recycling rate from 0% to 100% also had the largest effect on solid waste results, ranging from 362 pounds at 0% recycling to 261 pounds at 100% recycling. For GWP, PET bottle recycling had the largest effect on results, ranging from 1,196 pounds of CO_2 equivalents at 0% recycling to 998 at 100% recycling. The parameter variation with the second largest effect on GWP results was the percent of the personal vehicle trip to the grocery store that was allocated to purchasing water. At an allocation of 1%, the total GWP was 1,016 pounds of CO_2 equivalents, compared to 1,187 pounds CO_2 equivalents when 10% of the trip impacts were allocated to purchasing water.

The sensitivity analysis focused on parameters associated directly with production, transport, and end-of-life management of the primary container. For most parameters, the ranges of variations in parameters evaluated in the TopRank analysis were selected to represent the analysts' initial estimates of ranges that could reasonably be expected to occur in practice (e.g., reusable containers may be filled one to three times daily). Other variations were evaluated as either/or scenarios (e.g., water is either treated with ozone or is not treated with ozone).

Bottled Water System

Table 2-6 presents the sensitivity analysis on the example PET bottle system. As noted above, the PET recycling rate (evaluated from 0 to 100% for recycling methodology 1) and the PET container weight (evaluated at +/- 10% of the average bottle weight) were among the top three contributors to results for all three metrics--energy, solid waste, and GWP. As a result, subscenarios evaluated in the analysis include alternative recycling methodologies. The actual range of sample container weights was subsequently reviewed and updated to include the newest lightweighted bottles available. The sensitivity analysis did not evaluate variations in weights of caps or weights of packaging; however, the contribution analysis shows that these system components make large enough contributions to results that variations in the weights of these items are also considered in the subscenarios.

Table 2-6. Sensitivity Analysis Relative to Example Bottled Water System

Rank	Input Name	Reference Setting	Variation	Input Value	Minimum Output Value	Input Value	Maximum Output Value	Min to Max Range
	ENERGY							
	Reference case MMBtu	**9.90**						(MMBtu)
1	PET Recycling Rate	62%	0-100%	100%	9.21	0%	12.0	2.84
2	PET Container Weight (g)	13.3	+/-10%	11.97	9.68	14.63	10.9	1.23
3	Grocery Trip Allocation (%)	4%	1-10%	1%	9.94	10%	11.0	1.05
4	Miles Bottler to Dist.	50	50-130	50	10.3	130	10.9	0.58
5	Miles Store to Home	5	5 to 10	5	10.3	10	10.8	0.47
6	Days Chilled	0	0 to 5	0	10.3	5	10.8	0.46
7	Miles Molder to Bottler	0	0-200	0	10.3	200	10.6	0.33
8	Ozone	1 = yes	0 = no	0	9.98	1	10.3	0.31
9	Cap Weight (g)	1.6	1.4-1.6	1.4	10.2	1.6	10.3	0.14
	SOLID WASTE							
	Reference case pounds of waste	**286**						(pounds)
1	PET Recycling Rate	62%	0-100%	100%	261	0%	362	101
2	PET Ctr Weight (g)	13.3	+/-10%	11.97	280	14.63	318	38.5
3	Days Chilled	0	0 to 5	0	299	5	307	8.31
4	Ozone	1 = yes	0 = no	0	294	1	299	5.53
5	Cap Weight (g)	1.6	1.4-1.6	1.4	295	1.6	299	3.99
	GLOBAL WARMING POTENTIAL							
	Reference case lb CO2 equiv	**1,121**						(lb CO2 eq)
1	PET Recycling Rate (%)	62%	0-100%	100%	998	0%	1,196	198
2	Grocery Trip Allocation (%)	4%	1-10%	1%	1,016	10%	1,187	171
3	PET Ctr Weight (g)	13.3	+/-10%	11.97	1,009	14.63	1,138	129
4	Miles Bottler to Distributor	50	50-130	50	1,073	130	1,169	95.3
5	Miles Store to Home	5	5 to 10	5	1,073	10	1,150	76.5
6	Days Chilled	0	0 to 5	0	1,073	5	1,143	69.6
7	Miles Molder to Bottler	0	0-200	0	1,073	200	1,127	53.9
8	Ozone	1 = yes	0 = no	0	1,027	1	1,073	46.4
9	Cap Weight (g)	1.6	1.4-1.6	1.4	1,063	1.6	1,073	10.8

The sensitivity analysis was based on Oregon purified municipal water transported relatively short distances from filler to user (50 to 130 miles). Subscenarios consider natural water from within Oregon, natural water transported longer distances to Oregon from other U.S. locations, and imported natural water. Another area for consideration is allocation of transport burdens for water shipped from island countries that are net importers of goods. In this case, the outgoing shipments of water could be considered as incidental utilization of empty cargo space on return trips of ships delivering goods to the island, since the return trips are necessary regardless of whether any products are exported.

From a material standpoint, the sensitivity analysis included water bottles made from PET with recycled content ranging from 0 to 25%. Subscenarios discussed later in this chapter also consider PLA and glass containers, as well as evaluating possible PLA composting and different assumptions about decomposition of landfilled PLA. Because NatureWorks purchases renewable energy credits to offset their use of purchased electricity, energy and emissions for these purchased credits are shown in the credits section, separately from the results for production of PLA.

Tap Water System

Table 2-7 presents sensitivity analysis for the example tap water system. As described previously, the results for this system are primarily driven by variations in parameters that influence container washing. These include the number of times the container is refilled per day, the number of days the container is used before it is washed, and the energy and water consumption of the dishwasher cycle. The size of container also influences washing: the larger the volume of the container, the fewer container fillings (and washings) are required per 1,000 gallons of water consumed. The contribution and sensitivity analysis showed that independent variations in these parameters significantly affected results. As a result, variations are considered in the subscenarios, including simultaneous variations in these parameters (e.g., filling a container more than once per day *and* washing it less frequently).

Table 2-7. Sensitivity Analysis Relative to Example Tap Water System

Rank	Input Name	Reference Setting	Variation	Input Value	Minimum Output Value	Input Value	Maximum Output Value	Min to Max Range
	ENERGY							
	Reference case MMBtu	**2.25**						(MMBtu)
1	Days Before Washed	1	1 to 7	7	0.65	1	2.25	1.61
2	Times Filled Per Day	1	1 to 3	3	0.76	1	2.25	1.49
3	High Water Wash	High = 1	+/- 10%	90%	2.06	110%	2.44	0.37
4	Years of Use	1	1 to 5	5	1.96	1	2.25	0.29
5	Ctr Recycling Rate	0%	0-100%	100%	2.11	0%	2.25	0.14
6	Ctr Weight (g)	100 g	+/- 10%	90	2.22	110	2.29	0.069
7	% Ice	0%	0-20%	0%	2.25	20%	2.28	0.027
	SOLID WASTE							
	Reference case pounds of waste	**47.8**						(pounds)
1	Times Filled Per Day	1	1 to 3	3	16.1	1	47.8	31.7
2	Days Before Washed	1	1 to 7	7	23.8	1	47.8	24.1
3	Years of Use	1	1 to 5	5	32.2	1	47.8	15.6
4	Ctr Recycling Rate (%)	0%	0-100%	100%	38.7	0%	47.8	9.08
5	High water wash	High = 1	+/- 10%	90%	45.0	110%	50.6	5.61
6	Ctr Weight (g)	100 g	+/- 10%	90	45.9	110	49.7	3.78
	GLOBAL WARMING POTENTIAL							
	Reference case lb CO2 equiv	**339**						(lb CO2 eq)
1	Days Before Washed	1	1 to 7	7	90.9	1	328	237
2	Times Filled Per Day	1	1 to 3	3	111	1	328	217
3	High Water Wash	High = 1	+/- 10%	90%	301	110%	356	55.4
4	Years of Use	1	1 to 5	5	289	1	328	39.2
5	Ctr Recycling Rate (%)	0%	0-100%	100%	308	0%	328	20.3
6	Ctr Weight	100 g	+/- 10%	90	324	110	333	9.50
7	% Ice	0%	0-20%	0%	328	20%	332	4.00

HOD Water System

Sensitivity analysis for ranges of parameter variations for the HOD system are shown in Table 2-8. Variations due to reusable container parameters have already been discussed in the tap water section, so only variables in HOD parameters have been highlighted in Table 2-8.

Of the HOD parameters, variations in HOD route miles and lifetime trip rates have the largest influence on results. The range of lifetime uses evaluated (20-50) is expected to cover the range of actual trip rates. Additional transport distances are evaluated in the subscenarios.

The sensitivity analysis results in Table 2-8 only evaluate polycarbonate bottles containing purified municipal water; further subscenarios also consider PET HOD bottles and natural water.

Table 2-8. Sensitivity Analysis Relative to Example HOD Water System

ENERGY

Rank	Reference case MMBtu Input Name	7.10 Reference Setting	Variation	Input Value	Minimum Output Value	Input Value	Maximum Output Value	Min to Max Range (MMBtu)
1	Days Before Washed	1	1 to 7	7	7.21	1	8.82	1.61
2	Times Filled Per day	1	1 to 3	3	7.33	1	8.82	1.49
3	HOD Route Miles	75	50 - 100	50	8.43	100	9.21	0.78
4	Ozone	1 = yes	0 = no	0	8.42	1	8.82	0.40
5	Jug Reuses	40	20 - 50	50	8.76	20	9.13	0.38
6	High Water Wash	High = 1	+/- 10%	0.9	8.63	1.1	9.01	0.38
7	Years of Use	1	1 to 5	5	8.53	1	8.82	0.29
8	Drinking Ctr Recycling Rate	0%	0-100%	100%	8.67	0%	8.82	0.14

SOLID WASTE

Rank	Reference case pounds of waste Input Name	114 Reference Setting	Variation	Input Value	Minimum Output Value	Input Value	Maximum Output Value	Min to Max Range (pounds)
1	Times Filled Per Day	1	1 to 3	3	96.3	1	128	31.7
2	Days Before Washed	1	1 to 7	7	104	1	128	24.1
3	Years of Use	1	1 to 5	5	112	1	128	15.6
4	Drinking Ctr Recycling Rate	0%	0-100%	100%	119	0%	128	9.08
5	Jug Reuses	40	20 - 50	50	127	20	135	8.15
6	Ozone	1 = yes	0 = no	0	121	1	128	7.18
7	High Water Wash	High = 1	+/- 10%	90%	125	110%	131	5.62
8	Drinking Ctr Weight	100 g	+/- 10%	90	126	110	130	3.78
9	HOD Route Miles	75	50 - 100	50	127	100	129	1.88
10	Jug Weight	750 g	+/- 10%	675	127	825	129	1.41

GLOBAL WARMING POTENTIAL

Rank	Reference case lb CO2 equiv Input Name	1,072 Reference Setting	Variation	Input Value	Minimum Output Value	Input Value	Maximum Output Value	Min to Max Range (lb CO2 eq)
1	Days Before Washed	1	1 to 7	7	1,096	1	1,334	238
2	Times Filled Per Day	1	1 to 3	3	1,116	1	1,334	218
3	HOD Route Miles	75	50 - 100	50	1,270	100	1,398	128
4	Ozone	1 = yes	0 = no	0	1,270	1	1,334	64.1
5	High Water Wash	High = 1	+/- 10%	90%	1,306	110%	1,362	55.5
6	Jug Reuses	40	20 - 50	50	1,326	20	1,375	49.9
7	Years of Use	1	1 to 5	5	1,295	1	1,334	39.2
8	Drinking Ctr Recycling Rate	0%	0-100%	100%	1,314	0%	1,334	20.3

Variations in chilling were not evaluated in the TopRank runs; however, in the contribution analysis HOD chilling was shown to make a large contribution to the results for HOD systems. Thus, variation in the energy requirements for operation of the chilling unit is evaluated in the subscenarios selected. Chilling energy per 1,000 gallons consumed also depends on the rate of consumption of the water. For example, a five-gallon HOD bottle used in a large office is likely to be emptied more quickly than an HOD bottle used in a small office or by a family, resulting in less chilling time (and energy) for the large office application. Variations in HOD use patterns are considered in the subscenarios.

SELECTION OF SUBSCENARIOS

Based on the results of the contribution analyses from the draft LCI (see Appendix 1) and sensitivity analyses on the three example drinking water systems, 48 subscenarios were selected to meet the following goals:

- To capture scenarios that are believed to best represent typical practices
- To demonstrate "best case" or "worst case" scenarios[25] for selected systems to see if results for the different drinking water systems (bottled, tap, HOD) overlap at practical extremes
- To explore compounding or offsetting effects of simultaneous variations in key parameters within systems
- To identify parameters that have a large effect on results
- To identify parameters that do not have a large effect on results at any level.

Because the results for the example systems showed higher results for the bottled water system, in most cases the selected subscenarios use conservative baseline estimates or assumptions for the bottled water system and less favorable baseline assumptions (e.g., one-year useful life, washing container after each use) for the reusable tap and HOD systems, to see if overlap is expected within the ranges of parameters that could occur for the different systems.

[25] In this chapter, "best case" and "worst case" are based on energy, solid waste, and GWP results. These do not necessarily translate into the most or least favorable results for other impact categories such as eutrophication or smog. Results for other impact categories are presented and discussed in Chapter 3.

Table 2-9 presents the 48 subscenarios that are analyzed in the LCI and in the life cycle impact assessment LCIA results presented in Chapter 3. Additional information that is useful in understanding the subscenario modeling includes the following:

- PLA is a relatively new technology. NatureWorks is the largest U.S. producer of PLA, and NatureWorks' process is the only PLA process for which life cycle data are available. NatureWorks has published baseline data for 2005 PLA production as well as a 2006 PLA production dataset that reflected the purchase of wind energy credits to offset fossil energy use and carbon dioxide emissions associated with the production of PLA. In 2009 NatureWorks indicated that they have stopped purchasing wind energy credits due to process improvements that have significantly reduced their energy and carbon dioxide emissions for PLA production.[26] Although NatureWorks has published bottom-line cradle-to-resin results for MJ of energy and kg of carbon dioxide equivalents released per kg of PLA for the improved (2009) process, process data are not available at a level of detail to support LCA modeling for this report. Therefore, PLA modeling in this report is based on the dataset for 2005 PLA production from corn published in the Ecoinvent database, which contains the necessary level of detail on process fuels and other flows to support LCA modeling.
- The "Water Processing" results reported in the tables include both the processing of the drinking water and the processing of water used for container washing.
- Modeling of the treatment of purified municipal water packaged in bottles and HOD containers includes municipal water treatment plus reverse osmosis, ozone, and UV treatments. Processing of water used for container washing includes standard municipal water treatment without any additional purification processes.
- For natural water, 90 percent is assumed to be treated with ozone and 50 percent treated with UV, based on information provided by a contact at the International Bottled Water Association.
- Drinking water is often chilled prior to consumption; however, chilling is not required to maintain the quality of drinking water. Unless specifically noted, the bottled water and tap water scenarios do not include chilling of the water. However, because HOD dispensing units normally include a chilling unit, operation of the chilling unit was included in the HOD system results. Results for chilling are shown separately in the tables so that comparisons of unchilled HOD water with unchilled bottled and tap water can also be made.
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[26] http://www.natureworksllc.com/news-and-events/press-releases/2009/02-10-09-ingeo-ecoprofile.aspx

Production of electricity is modeled based on the grid relevant to the location where each processing step takes place. Therefore, different scenarios show some differences in results that are due solely to differences in the location where the process occurs, not to differences in the process itself. For example, because Oregon electricity uses more hydropower compared to the national average grid, a process modeled based on Oregon electricity shows lower total energy and emissions compared to the same process modeled based on the U.S. average grid.

- Differences in scenario results can be understood by considering the effect of the scenario parameters on the functional unit, that is, delivery of 1,000 gallons of drinking water. For example, in the reusable container scenarios, water processing requirements and dishwasher operation requirements are lower for larger volume drinking containers. The larger the volume of the container, the fewer the container fillings (and washings) required for consumption of 1,000 gallons of water.

Table 2-9. Subscenarios Analyzed
(Gray shading in cells indicates parameters that are the same as those shown in the first column of that row)

Subscenarios for Bottled Water	PET ref R1 **1**	PET ref R2 **2**	PET ref R3 **3**	PET 1 liter **4**	PET 8 oz **5**	PET light **6**	PET light, low mold **7**	25% rPET R1 **8**	25% rPET R2 **9**	25% rPET R3 **10**	PLA 0 decomp **11**	PLA 100 decomp **12**	PLA compost **13**
Bottle material	PET										PLA	PLA	PLA
Bottle weight (g)	13.3	13.3	13.3	39.1	12.3	9.8	9.8				13.7	13.7	13.7
Bottle volume (fl oz)	16.9			33.8	8								
PET recycled content	0%							25%	25%	25%	0%	0%	0%
Water source/distance	OR, 50 mi												
Water in bottle	purified municipal*												
Molded bottle transport	none												
Bottles rinsed before filling	none												
Home to retail	5 miles												
Trip fuel use allocated to water	4%												
Chilling	none												
Recycling	62%												
Recycling allocation method	1	2	3					1	2	3			
Bottle molding energy (kWh/thou lb resin)	PET molding energy						10% lower PET molding energy				PLA molding energy	PLA molding energy	PLA molding energy
Cap weight (g)	1.6			2.8	1.4	1.4	1.4						
Corrug pkg weight/bottle (g)	2.01												
Film pkg weight/bottle (g)	1.41												
Ocean transp allocation for imports	wt-based												
PLA composting	0%												100%
PLA decomposition	0%										0%	100%	

Subscenarios for Bottled Water (cont)	PET nat **14**	PET Maine nat **15**	PET Fiji nat **16**	PET Fiji free sea **17**	Glass France **18**	PET 500 mi empty **19**	PET 100% store trip **20**	PET refrig **21**	PET 37%R **22**	PET best **23**	PET worst **24**	PLA best **25**
Bottle material	PET				Glass					PET	PET	PLA
Bottle weight (g)	13.3		27.5	27.5	242					9.8	12.3	10.1
Bottle volume (fl oz)	16.9				12.1					16.9	8	16.9
PET recycled content	0%									25%	0%	0%
Water source/distance	OR, 130	Maine	Fiji	Fiji	France	OR 50				OR, 20 mi	Maine	OR, 20 mi
Water in bottle	nat, 90% ozone disinfect, 50% UV disinfect	nat, 90% ozone disinfect, 50% UV disinfect	nat, 100% UV	nat, 100% UV	nat, 90% ozone disinfect, 50% UV disinfect	purified municipal*				natural water, UV treatment	natural water, 100% ozone + UV treatment	natural water, UV treatment
Molded bottle transport	none					500				none	500	none
Bottles rinsed before filling	none									none	yes	none
Home to retail	5 miles									5 miles	5 miles	5 miles
Trip fuel use allocated to water	4%						100%			0%	100%	0%
Chilling	none							3.5 day in home refrig		none	1 week home refrig	none
Recycling	62%								37%	100%	0%	0%
Recycling allocation method	1									3	1	3
Bottle molding energy (kWh/thou lb resin)	PET molding energy									10% lower kWh	PET molding energy	10% lower than std PLA
Cap weight (g)	1.6		2.6	2.6	13.5					1.4	1.4	1.4
Corrug pkg weight/bottle (g)	2.01									0	2.20	0
Film pkg weight/bottle (g)	1.41									1.45	1.54	1.45
Ocean transp allocation for imports	wt-based		wt-based ocean	discounted ocean	wt-based ocean							
PLA composting	0%											
PLA decomposition	0%											0%

* Purified municipal water treatment is modeled as reverse osmosis, ozone, and ultraviolet.

Table 2-9. Subscenarios Analyzed (continued)
(Gray shading in cells indicates parameters that are the same as those shown in the first column of that row)

Subscenarios for Tap Water with Reusable Container	Tap Al ref **26**	Tap PET **27**	Tap steel **28**	Tap glass **29**	Tap Al 5 yr **30**	Tap Al 100%R **31**	Tap Al 2x fill **32**	Tap Al wk wash **33**	Tap Al low wash **34**	Tap Al 1/2 full wash **35**	Tap Al ice **36**	Tap best **37**
Reusable drinking container	Virgin Aluminum	Virgin PET	Steel	Drinking Glass								Virgin PET
Container weight	100 g	104 g	227 g	245 g								104 g
Container volume (fl oz)	20 oz	32 oz	27 oz	16 oz								32 oz
Years of use	1 yr				5 yrs							5 yrs
Recycling of drinking container	0%					100%						0%
Recycling allocation method	1											3
Container fillings/day	1						2					2
Days used before washed	1 day							7				7
High or low water wash	high wash								low wash	high wash, half full		low wash
Chilled	no										50% ice	no

Subscenarios for HOD Water with Reusable Container	HOD ref **38**	HOD PET **39**	HOD heavy **40**	HOD 30 trip **41**	HOD nat **42**	HOD 200 mi distrib **43**	HOD 50 mi route **44**	HOD low chill **45**	HOD high chill **46**	HOD best **47**	HOD worst **48**
Reusable drinking container	Aluminum									Virgin PET	Drinking Glass
Container weight	100 g									104 g	245 g
Years of use	1 yr									5 yrs	1 yr
Recycling of drinking container	0%									0%	0%
Recycling allocation method	1									3	1
Container fillings/day	1									2	1
Days used before washed	1 day									7	1 day
High or low water wash	high wash									low wash	high wash, half full
HOD bottle type	Virgin Polycarb	Virgin PET								Virgin Polycarb	Virgin PET
HOD bottle weight	750 g		10% higher weight							750 g	10% higher weight
Lifetime reuses	40			30						40	30
Water in bottle	purified municipal*				nat, 90% ozone disinfect, 50% UV disinfect					natural water, UV treatment	purified municipal*
Water source/distance	OR, 50 mi					OR, 200 mi				OR, 50 mi	OR, 200 mi
Route miles	75						50			50	100
Chiller base energy use (kWh/day)	0.16								20% higher kWh	0.16	20% higher kWh
Gal HOD water consumed/day of chilling	0.67							1	0.67	1	0.67

* Purified municipal water treatment is modeled as reverse osmosis, ozone, and ultraviolet.

SUBSCENARIO ANALYSIS

Energy Results

Energy results by life cycle stage and by energy category for the 48 drinking water subscenarios are presented in Table 2-10. Energy results by life cycle stage are presented graphically for all bottled water systems in Figure 2-1. Figure 2-2 shows the same results but with long-distance transport scenarios excluded in order to show greater detail on results by life cycle stage. Figure 2-3 shows results by life cycle stage for tap water and HOD subscenarios. In each figure, each scenario is given a short name designating the main difference from the reference scenario. Table 2-9 shows the modeling details for each numbered subscenario.

Net energy results (after adjustment for end-of-life credits for recycling of containers and corrugated packaging) are shown in Figure 2-4 for bottled water scenarios and in Figure 2-5 for tap and HOD water scenarios.

Bottled Water Energy. Production of bottles accounts for the majority of energy consumption for all subscenarios except those involving long-distance transport (scenario 15 for water trucked from Maine, scenarios 16 and 17 for water from Fiji, scenario 18 for bottled water imported from France in glass bottles). Comparing the transportation energy in scenarios 15 and 16 shows that trucking water cross-country (scenario 15) requires more energy than transporting water longer distances by ocean and a shorter distance by truck (scenario 16). The very high transportation energy for scenario 18 is due not only to the long distances the water is transported but also to the glass bottles' contribution to the load weight.

On a thousand gallon basis, the energy requirements for PET bottle production are highest for the 8-ounce bottle (scenario 5) which has the highest ratio of bottle weight to weight of water in the bottle, and the bottles in the Fiji import scenarios. In the Fiji imported water scenarios, the weight of the bottle is based on the weight of a sample bottle from Fiji, which was heavier than the average domestic bottle weight. Energy requirements for producing PLA bottles (scenarios 11 through 14 and 25) are somewhat lower than the energy for producing the same size PET container. Glass has lower burdens per pound than the other bottle materials; however, the much greater weight of the glass bottles results in a much higher total energy requirement for production of glass bottles.

In addition to the bottles themselves, the bottle lids and secondary packaging make significant contributions to the energy results. On average across all subscenarios, production of caps and secondary packaging each accounted for 12 percent of total energy. Originally, case packaging for bottled water was all in corrugated trays with film overwrap, but many bottlers have lightweighted by switching to a corrugated pad with film overwrap. Lightweighting efforts continue, with some bottlers eliminating corrugated entirely and using all-film case packaging. Secondary packaging results in most scenarios are based on the average weights of corrugated and film for these three packaging configurations. For the lightest (all-film) secondary packaging scenario, secondary packaging accounts for about 2.5 percent of total energy requirements.

Scenarios 1 through 3 show the same virgin bottled water scenario evaluated for each of the three recycling methodologies. Figure 2-2 shows that the recycling energy credit is greatest for methodology 3, because this method transfers all the virgin production and disposal burdens for the recovered material to the user system. Methodology 1, the open-loop methodology, shares the energy credits between the bottle system and the system using the recovered bottle material. Methodology 2 shows no recycling credits for recovered bottles, since this method assigns all the material production burdens to the first system using the material (the bottle system). Methodology 1 has the highest solid waste results for the producer system, since the disposal burdens for the material are shared between the systems producing and using the recycled material. Similar observations can be made for scenarios 8 through 10 for a 25% recycled content bottle evaluated for all three recycling methodologies.

Tap Water Energy. At first glance, the large fluctuations in results for the tap water scenarios appear somewhat random, but the majority of the variation can be understood in terms of each variable's effect on container washing, which dominates the results for all tap water scenarios. The number of drinking container washings per thousand gallons of water consumed varies inversely with the size of the containers, the number of times the container is filled before washing, and the number of days the container is used before washing. The drinking glass system (scenario 29) has the lowest energy use for container manufacture but has the highest washing requirements because it is smaller than the other reusable containers and requires more container washings per thousand gallons of water consumed compared to the larger containers when all are modeled as being filled once daily and washed after one filling. Similarly, doubling the daily number of container fills or washing the container every two days instead of daily reduces the washing requirements by half. Washing energy requirements are highest for scenario 35, where washing is modeled based on washing containers in a high water use dishwasher that is run when it is only half full.

HOD Water Energy. For HOD water scenarios, the three life cycle stages consistently making the largest contributions to overall energy use are distribution of HOD containers, home washing of the reusable drinking containers (described in the tap water section), and chilling of the HOD water using a chilling base unit. Industrial washing of HOD containers between uses accounts for only 2 percent on average of total energy use. Because the energy for producing the HOD container is divided over the total number of lifetime uses, the energy allocated to 1,000 gallons is small, averaging 6 percent of total energy for the HOD scenarios.

Profiles by Energy Source. Table 2-11 presents energy results for each system by energy sources used for each life cycle stage. As discussed previously for the example scenarios, fossil fuels account for the majority of energy use for each system, although the profiles are different for each drinking water system.

Natural gas and petroleum account for a larger percentage of fuel use for the bottled water system than for the other systems, due to the use of these resources not only as process and transportation fuels but also as material feedstocks for the production of the plastic resin in the PET bottles and bottle caps.

Coal and natural gas dominate fossil fuel for the tap water systems, mainly due to the use of electricity for dishwasher operation and electricity and natural gas use for heating the water used to wash the containers. Petroleum is only a small percentage of total energy use for the tap water system since this system does not require the use of vehicles to get the water to consumers. Electricity is used for pumped distribution of tap water.

The HOD system has significant percentages of energy from natural gas, petroleum, and coal. Coal use is attributed to the electricity used for operating the chiller unit and washing the HOD containers and reusable containers between fillings, while most of the natural gas is used for water heating for the washing operations. Most of the petroleum use is by the trucks making the route deliveries of HOD bottles to customers and backhauling empty HOD bottles to the bottling plant for refilling.

Table 2-10. Energy by Category for Example Drinking Water Systems (million Btu per 1,000 gallons)

		Process	Transport	Energy of Material Resource (EMR)	NET
PET ref R1					
1	Credit for recycling (method 1)	-1.08	-0.051	-1.13	-2.25
	Production of PET bottle	4.08	0.24	3.64	7.96
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.46	0.031	0.63	1.12
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.17	0.20	0	0.37
	End of life management - caps & closures	-0.010	0.0088	0	-0.0011
	End of life management - secondary packaging	-0.026	0.012	0	-0.014
	TOTAL	**4.88**	**1.31**	**3.71**	**9.90**
	Percent by category	49%	13%	37%	100%
PET ref R2					
2	Credit for recycling (method 2)	0	0	0	0
	Production of PET bottle	4.08	0.24	3.64	7.96
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.46	0.031	0.63	1.12
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	-0.016	0.028	0	0.012
	End of life management - caps & closures	-0.010	0.0088	0	-0.0011
	End of life management - secondary packaging	-0.017	0.0065	0	-0.010
	TOTAL	**5.78**	**1.19**	**4.83**	**11.8**
	Percent by category	49%	10%	41%	100%
PET ref R3					
3	Credit for recycling (method 3)	-2.12	-0.10	-2.22	-4.44
	Production of PET bottle	4.08	0.24	3.64	7.96
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.46	0.031	0.63	1.12
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.39	0.32	0	0.71
	End of life management - caps & closures	-0.010	0.0088	0	-0.0011
	End of life management - secondary packaging	-0.016	0.013	0	-0.0030
	TOTAL	**4.06**	**1.39**	**2.62**	**8.07**
	Percent by category	50%	17%	32%	100%
PET 1 liter					
4	Credit for recycling (method 1)	-1.45	-0.069	-1.66	-3.17
	Production of PET bottle (1 liter)	6.00	0.35	5.35	11.7
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.40	0.027	0.55	0.98
	Production of secondary packaging	0.34	0.021	0.28	0.64
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (4% allocated to water)	0	0.24	0	0.24
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.26	0.29	0	0.55
	End of life management - caps & closures	-0.0087	0.0077	0	-9.5E-04
	End of life management - secondary packaging	-0.013	0.0060	0	-0.0068
	TOTAL	**6.13**	**1.24**	**4.52**	**11.9**
	Percent by category	52%	10%	38%	100%

Table 2-10. Energy by Category for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Process	Transport	Energy of Material Resource (EMR)	NET
PET 8 oz					
5	Credit for recycling (method 1)	-2.13	-0.10	-2.20	-4.43
	Production of PET bottle (8 oz)	7.97	0.47	7.10	15.5
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.85	0.057	1.16	2.07
	Production of secondary packaging	1.42	0.088	1.20	2.71
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.37	0	0.37
	Consumer transport (4% allocated to water)	0	0.99	0	0.99
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.34	0.39	0	0.73
	End of life management - caps & closures	-0.018	0.016	0	-0.0020
	End of life management - secondary packaging	-0.054	0.025	0	-0.029
	TOTAL	**9.00**	**2.31**	**7.27**	**18.6**
	Percent by category	48%	12%	39%	100%
PET light					
6	Credit for recycling (method 1)	-0.83	-0.039	-0.83	-1.70
	Production of PET bottle (lightweighted)	3.01	0.18	2.68	5.86
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.40	0.027	0.55	0.98
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.13	0.15	0	0.28
	End of life management - caps & closures	-0.0087	0.0077	0	-9.5E-04
	End of life management - secondary packaging	-0.026	0.012	0	-0.014
	TOTAL	**3.95**	**1.20**	**2.97**	**8.12**
	Percent by category	49%	15%	37%	100%
PET light, low mold					
7	Credit for recycling (method 1)	-0.83	-0.039	-0.83	-1.70
	Production of PET bottle (lightweight, lower molding energy)	2.93	0.18	2.68	5.79
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.40	0.027	0.55	0.98
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.13	0.15	0	0.28
	End of life management - caps & closures	-0.0087	0.0077	0	-9.5E-04
	End of life management - secondary packaging	-0.026	0.012	0	-0.014
	TOTAL	**3.88**	**1.20**	**2.97**	**8.05**
	Percent by category	48%	15%	37%	100%
25% rPET R1					
8	Credit for recycling (method 1)	-0.96	-0.045	-0.99	-1.99
	Production of PET bottle (25% recycled content)	3.78	0.25	3.18	7.21
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.46	0.031	0.63	1.12
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.18	0.19	0	0.37
	End of life management - caps & closures	-0.010	0.0088	0	-0.0011
	End of life management - secondary packaging	-0.026	0.012	0	-0.014
	TOTAL	**4.70**	**1.32**	**3.39**	**9.41**
	Percent by category	50%	14%	36%	100%

Table 2-10. Energy by Category for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Process	Transport	Energy of Material Resource (EMR)	NET
25% rPET R2					
9	Credit for recycling (method 2)	0	0	0	0
	Production of PET bottle (25% recycled content)	3.48	0.25	2.73	6.46
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.46	0.031	0.63	1.12
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	-0.016	0.028	0	0.012
	End of life management - caps & closures	-0.010	0.0088	0	-0.0011
	End of life management - secondary packaging	-0.017	0.0065	0	-0.010
	TOTAL	**5.18**	**1.20**	**3.92**	**10.3**
	Percent by category	50%	12%	38%	100%
25% rPET R3					
10	Credit for recycling (method 3)	-2.12	-0.10	-2.22	-4.44
	Production of PET bottle (25% recycled content)	4.08	0.24	3.64	7.96
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.46	0.031	0.63	1.12
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.39	0.32	0	0.71
	End of life management - caps & closures	-0.010	0.0088	0	-0.0011
	End of life management - secondary packaging	-0.016	0.013	0	-0.0030
	TOTAL	**4.06**	**1.39**	**2.62**	**8.07**
	Percent by category	50%	17%	32%	100%
PLA 0 decomp					
11	Credit for recycling (method 1)	-0.14	-0.0056	-4.3E-05	-0.15
	Production of PLA bottle	5.27	0.11	0.047	5.42
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.46	0.031	0.63	1.12
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 0% decomposition	-0.031	0.076	0	0.045
	End of life management - caps & closures	-0.010	0.0088	0	-0.0011
	End of life management - secondary packaging	-0.026	0.012	0	-0.014
	TOTAL	**5.48**	**1.11**	**1.24**	**7.83**
	Percent by category	70%	14%	16%	100%
PLA 100 decomp					
12	Credit for recycling (method 1)	-0.14	-0.0056	-4.3E-05	-0.15
	Production of PLA bottle	5.27	0.11	0.047	5.42
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.46	0.031	0.63	1.12
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 100% decomposition	-0.48	0.076	0	-0.40
	End of life management - caps & closures	-0.010	0.0088	0	-0.0011
	End of life management - secondary packaging	-0.026	0.012	0	-0.014
	TOTAL	**5.03**	**1.11**	**1.24**	**7.38**
	Percent by category	68%	15%	17%	100%

Table 2-10. Energy by Category for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Process	Transport	Energy of Material Resource (EMR)	NET
PLA compost					
13	Credit for recycling (method 1)	-0.14	-0.0056	-4.3E-05	-0.15
	Production of PLA bottle	5.27	0.11	0.047	5.42
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.46	0.031	0.63	1.12
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 100% composting	-0.049	0.076	0	0.027
	End of life management - caps & closures	-0.010	0.0088	0	-0.0011
	End of life management - secondary packaging	-0.026	0.012	0	-0.014
	TOTAL	**5.46**	**1.11**	**1.24**	**7.81**
	Percent by category	70%	14%	16%	100%
PET nat					
14	Credit for recycling (method 1)	-1.08	-0.051	-1.13	-2.25
	Production of PET bottle	4.08	0.24	3.64	7.96
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.46	0.031	0.63	1.12
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (natural)	0.28	0	0	0.28
	Filling	0.022	0	0	0.022
	Distribution of filled containers (130 mi)	0	0.94	0	0.94
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0	0	0
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.17	0.20	0	0.37
	End of life management - caps & closures	-0.010	0.0088	0	-0.0011
	End of life management - secondary packaging	-0.026	0.012	0	-0.014
	TOTAL	**4.58**	**1.89**	**3.71**	**10.2**
	Percent by category	45%	19%	36%	100%
PET Maine nat					
15	Credit for recycling (method 1)	-1.08	-0.051	-1.13	-2.25
	Production of PET bottle	4.37	0.24	3.64	8.24
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.46	0.031	0.63	1.12
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (natural)	0.36	0	0	0.36
	Filling	0.029	0	0	0.029
	Distribution of filled containers from Maine	0	23.8	0	23.8
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0	0	0
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.17	0.20	0	0.37
	End of life management - caps & closures	-0.010	0.0088	0	-0.0011
	End of life management - secondary packaging	-0.026	0.012	0	-0.014
	TOTAL	**4.95**	**24.7**	**3.71**	**33.4**
	Percent by category	15%	74%	11%	100%
PET Fiji nat					
16	Credit for recycling (method 1)	-2.08	-0.10	-2.33	-4.50
	Production of PET bottle	9.03	0.50	7.52	17.0
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.75	0.050	1.02	1.82
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (natural)	5.3E-04	0	0	5.3E-04
	Filling	0.029	0	0	0.029
	Distribution of filled containers from Fiji	0	13.9	0	13.9
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0	0	0
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.36	0.41	0	0.77
	End of life management - caps & closures	-0.016	0.014	0	-0.0018
	End of life management - secondary packaging	-0.026	0.012	0	-0.014
	TOTAL	**8.72**	**15.3**	**6.78**	**30.8**
	Percent by category	28%	50%	22%	100%

Table 2-10. Energy by Category for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Process	Transport	Energy of Material Resource (EMR)	NET
PET Fiji free sea					
17	Credit for recycling (method 1)	-2.08	-0.10	-2.33	-4.50
	Production of PET bottle	9.03	0.50	7.52	17.0
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.75	0.050	1.02	1.82
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (natural)	5.3E-04	0	0	5.3E-04
	Filling	0.029	0	0	0.029
	Distribution of filled containers from Fiji (discounted ocean)	0	6.90	0	6.90
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0	0	0
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.36	0.41	0	0.77
	End of life management - caps & closures	-0.016	0.014	0	-0.0018
	End of life management - secondary packaging	-0.026	0.012	0	-0.014
	TOTAL	**8.72**	**8.30**	**6.78**	**23.8**
	Percent by category	37%	35%	28%	100%
Glass France					
18	Credit for recycling (method 1)	-9.07	-0.31	-6.1E-05	-9.38
	Production of glass bottle	23.2	0.81	0	24.0
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	5.42	0.37	7.41	13.2
	Production of secondary packaging	0.94	0.058	0.79	1.79
	Water processing (natural)	0.30	0	0	0.30
	Filling	0.025	0	0	0.025
	Distribution of filled containers from France	0	42.1	0	42.1
	Consumer transport (4% allocated to water)	0	0.66	0	0.66
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0	0	0
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 74% recycling	0.76	0.60	0	1.35
	End of life management - caps & closures	-0.12	0.10	0	-0.013
	End of life management - secondary packaging	-0.036	0.017	0	-0.019
	TOTAL	**21.4**	**44.4**	**8.20**	**74.0**
	Percent by category	29%	60%	11%	100%
PET 500 mi empty					
19	Credit for recycling (method 1)	-1.08	-0.051	-1.13	-2.25
	Production of PET bottle (molded offsite)	4.08	1.06	3.64	8.78
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.46	0.031	0.63	1.12
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (4% allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.17	0.20	0	0.37
	End of life management - caps & closures	-0.010	0.0088	0	-0.0011
	End of life management - secondary packaging	-0.026	0.012	0	-0.014
	TOTAL	**4.88**	**2.14**	**3.71**	**10.7**
	Percent by category	46%	20%	35%	100%
PET 100% store trip					
20	Credit for recycling (method 1)	-1.08	-0.051	-1.13	-2.25
	Production of PET bottle	4.08	0.24	3.64	7.96
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.46	0.031	0.63	1.12
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (100% of trip allocated to water)	0	11.7	0	11.7
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.17	0.20	0	0.37
	End of life management - caps & closures	-0.010	0.0088	0	-0.0011
	End of life management - secondary packaging	-0.026	0.012	0	-0.014
	TOTAL	**4.88**	**12.6**	**3.71**	**21.1**
	Percent by category	23%	59%	18%	100%

Table 2-10. Energy by Category for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Process	Transport	Energy of Material Resource (EMR)	NET
PET refrig					
21	Credit for recycling (method 1)	-1.08	-0.051	-1.13	-2.25
	Production of PET bottle	4.08	0.24	3.64	7.96
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.46	0.031	0.63	1.12
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (4% of trip allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (3.5 days home refrig)	0.33	0	0	0.33
	End of life management - bottles @ 62% recycling	0.17	0.20	0	0.37
	End of life management - caps & closures	-0.010	0.0088	0	-0.0011
	End of life management - secondary packaging	-0.026	0.012	0	-0.014
	TOTAL	**5.21**	**1.31**	**3.71**	**10.2**
	Percent by category	51%	13%	36%	100%
PET 37%R					
22	Credit for recycling (method 1)	-0.70	-0.033	-0.67	-1.40
	Production of PET bottle	4.08	0.24	3.64	7.96
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.46	0.031	0.63	1.12
	Production of secondary packaging	0.67	0.042	0.57	1.28
	Water processing (purified municipal)	0.58	1.1E-05	2.6E-05	0.58
	Filling	0.022	0	0	0.022
	Distribution of filled containers (50 mi)	0	0.36	0	0.36
	Consumer transport (4% of trip allocated to water)	0	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0019	1.6E-06	0	0.0019
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 37% recycling	0.087	0.15	0	0.24
	End of life management - caps & closures	-0.010	0.0088	0	-0.0011
	End of life management - secondary packaging	-0.026	0.012	0	-0.014
	TOTAL	**5.17**	**1.28**	**4.16**	**10.6**
	Percent by category	49%	12%	39%	100%
PET best					
23	Credit for recycling (method 3)	-2.19	-0.11	-2.63	-4.93
	Production of PET bottle (lightweight, 25% recycl cont)	2.93	0.18	2.68	5.79
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.40	0.027	0.55	0.98
	Production of secondary packaging (film only)	0.31	0.028	0.58	0.92
	Water processing (natural)	4.2E-04	0	0	4.2E-04
	Filling	0.022	0	0	0.022
	Distribution of filled containers (20 mi)	0	0.14	0	0.14
	Consumer transport (0% of trip allocated to water)	0	0.0032	0	0.0032
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0	0	0
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 100% recycling	0.48	0.35	0	0.83
	End of life management - caps & closures	-0.0087	0.0077	0	-9.5E-04
	End of life management - secondary packaging	-0.012	0.0052	0	-0.0064
	TOTAL	**1.95**	**0.64**	**1.18**	**3.76**
	Percent by category	52%	17%	31%	100%
PET worst					
24	Credit for recycling (method 1)	-0.33	-0.013	-1.0E-04	-0.34
	Production of PET bottle (8 oz, molded off-site)	8.53	1.29	7.10	16.9
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.85	0.057	1.16	2.07
	Production of secondary packaging	1.56	0.096	1.31	2.96
	Water processing (natural)	0.40	0	0	0.40
	Filling	0.029	0	0	0.029
	Distribution of filled containers from Maine	0	24.6	0	24.6
	Consumer transport (100% of trip allocated to water)	0	24.7	0	24.7
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	7.6E-05	6.5E-08	0	7.6E-05
	Chilling (1 wk home refrig)	1.37	0	0	1.37
	End of life management - bottles @ 0% recycling	-0.081	0.14	0	0.062
	End of life management - caps & closures	-0.018	0.016	0	-0.0020
	End of life management - secondary packaging	-0.059	0.028	0	-0.031
	TOTAL	**12.3**	**51.0**	**9.58**	**72.8**
	Percent by category	17%	70%	13%	100%

Table 2-10. Energy by Category for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Process	Transport	Energy of Material Resource (EMR)	NET
PLA best					
25	Credit for recycling (method 3)	0	0	0	0
	Production of PLA bottle	3.80	0.081	0.035	3.92
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.40	0.027	0.55	0.98
	Production of secondary packaging (film only)	0.31	0.028	0.58	0.92
	Water processing (natural)	4.2E-04	0	0	4.2E-04
	Filling	0.022	0	0	0.022
	Distribution of filled containers (20 mi)	0	0.14	0	0.14
	Consumer transport (0% of trip allocated to water)	0	0.0032	0	0.0032
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0	0	0
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 0% decomposition	-0.023	0.056	0	0.033
	End of life management - caps & closures	-0.0087	0.0077	0	-9.5E-04
	End of life management - secondary packaging	-0.012	0.0052	0	-0.0064
	TOTAL	**3.53**	**0.35**	**1.17**	**5.04**
	Percent by category	70%	7%	23%	100%
Tap Al ref					
26	Credit for recycling (method 1)	0	0	0	0
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.0083	5.6E-04	0.011	0.020
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	0.028	1.2E-05	2.8E-05	0.028
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	1.85	0	0	1.85
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0062	5.3E-06	0	0.0062
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	4.3E-04	9.1E-04	0	0.0013
	End of life management - caps & closures	-1.8E-04	1.6E-04	0	-2.0E-05
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**2.18**	**0.029**	**0.048**	**2.25**
	Percent by category	97%	1%	2%	100%
Tap PET					
27	Credit for recycling (method 1)	0	0	0	0
	Production of reusable drinking container (32 oz PET, 1 yr use)	0.056	0.0038	0.041	0.10
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.0075	5.0E-04	0.010	0.018
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	0.023	1.0E-05	2.4E-05	0.023
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	1.16	0	0	1.16
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0039	3.3E-06	0	0.0039
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	-4.7E-04	8.3E-04	0	3.6E-04
	End of life management - caps & closures	-1.6E-04	1.4E-04	0	-1.8E-05
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**1.25**	**0.0053**	**0.052**	**1.31**
	Percent by category	96%	0%	4%	100%
Tap steel					
28	Credit for recycling (method 1)	0	0	0	0
	Production of reusable drinking container (27 oz steel, 1 yr use)	0.11	0.021	0	0.13
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.018	0.0012	0.025	0.044
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	0.025	1.1E-05	2.5E-05	0.025
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	1.37	0	0	1.37
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0046	3.9E-06	0	0.0046
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	3.2E-04	0.0014	0	0.0017
	End of life management - caps & closures	-3.9E-04	3.5E-04	0	-4.3E-05
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**1.53**	**0.024**	**0.025**	**1.57**
	Percent by category	97%	2%	2%	100%

Table 2-10. Energy by Category for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Process	Transport	Energy of Material Resource (EMR)	NET
Tap glass					
29	Credit for recycling (method 1)	0	0	0	0
	Production of reusable drinking container (16 oz drinking glass, 1 yr use)	0.050	0.0017	0	0.052
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0	0	0	0
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	0.031	1.3E-05	3.2E-05	0.031
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	2.32	0	0	2.32
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0077	6.6E-06	0	0.0078
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	1.2E-04	0.0010	0	0.0011
	End of life management - caps & closures	0	0	0	0
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**2.41**	**0.0028**	**3.2E-05**	**2.41**
	Percent by category	100%	0%	0%	100%
Tap Al 5 yr					
30	Credit for recycling (method 1)	0	0	0	0
	Production of reusable drinking container (20 oz aluminum, 5 yrs use)	0.056	0.0054	0.0073	0.068
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.0017	1.1E-04	0.0023	0.0040
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	0.028	1.2E-05	2.8E-05	0.028
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	1.85	0	0	1.85
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0062	5.3E-06	0	0.0062
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	8.6E-05	1.8E-04	0	2.7E-04
	End of life management - caps & closures	-3.6E-05	3.2E-05	0	-3.9E-06
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**1.95**	**0.0057**	**0.0096**	**1.96**
	Percent by category	99%	0%	0%	100%
Tap Al 100%R					
31	Credit for recycling (method 1)	-0.13	-0.0068	-0.018	-0.16
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.0083	5.6E-04	0.011	0.020
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	0.028	1.2E-05	2.8E-05	0.028
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	1.85	0	0	1.85
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0062	5.3E-06	0	0.0062
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 100% recycling	0.014	0.0016	9.8E-04	0.017
	End of life management - caps & closures	-1.8E-04	1.6E-04	0	-2.0E-05
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**2.06**	**0.022**	**0.031**	**2.11**
	Percent by category	97%	1%	1%	100%
Tap Al 2x fill					
32	Credit for recycling (method 1)	0	0	0	0
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.14	0.013	0.018	0.17
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.0042	2.8E-04	0.0057	0.010
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	0.022	9.4E-06	2.2E-05	0.022
	Filling (reusable drinking container filled twice daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.93	0	0	0.93
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0031	2.6E-06	0	0.0031
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	2.1E-04	4.5E-04	0	6.7E-04
	End of life management - caps & closures	-9.0E-05	8.0E-05	0	-9.8E-06
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**1.10**	**0.014**	**0.024**	**1.13**
	Percent by category	97%	1%	2%	100%

Table 2-10. Energy by Category for Example Drinking Water Systems (million Btu per 1,000 gallons)

		Process	Transport	Energy of Material Resource (EMR)	NET
Tap Al wk wash					
33	Credit for recycling (method 1)	0	0	0	0
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.0083	5.6E-04	0.011	0.020
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	0.017	7.5E-06	1.7E-05	0.017
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (once/week, high water use)	0.26	0	0	0.26
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	8.9E-04	7.5E-07	0	8.9E-04
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	4.3E-04	9.1E-04	0	0.0013
	End of life management - caps & closures	-1.8E-04	1.6E-04	0	-2.0E-05
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**0.57**	**0.029**	**0.048**	**0.65**
	Percent by category	88%	4%	7%	100%
Tap Al low wash					
34	Credit for recycling (method 1)	0	0	0	0
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.0083	5.6E-04	0.011	0.020
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	0.019	8.2E-06	1.9E-05	0.019
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, low water use)	1.03	0	0	1.03
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0018	1.5E-06	0	0.0018
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	4.3E-04	9.1E-04	0	0.0013
	End of life management - caps & closures	-1.8E-04	1.6E-04	0	-2.0E-05
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**1.33**	**0.029**	**0.048**	**1.41**
	Percent by category	95%	2%	3%	100%
Tap Al 1/2 full wash					
35	Credit for recycling (method 1)	0	0	0	0
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.0083	5.6E-04	0.011	0.020
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	0.040	1.8E-05	4.1E-05	0.040
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (high water, half full load)	3.71	0	0	3.71
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.012	1.1E-05	0	0.012
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	4.3E-04	9.1E-04	0	0.0013
	End of life management - caps & closures	-1.8E-04	1.6E-04	0	-2.0E-05
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**4.05**	**0.029**	**0.048**	**4.12**
	Percent by category	98%	1%	1%	100%
Tap Al ice					
36	Credit for recycling (method 1)	0	0	0	0
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.0083	5.6E-04	0.011	0.020
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	0.035	1.5E-05	3.6E-05	0.035
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	1.85	0	0	1.85
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0.0062	5.3E-06	0	0.0062
	Chilling (50% ice)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	4.3E-04	9.1E-04	0	0.0013
	End of life management - caps & closures	-1.8E-04	1.6E-04	0	-2.0E-05
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**2.18**	**0.029**	**0.048**	**2.26**
	Percent by category	97%	1%	2%	100%

Table 2-10. Energy by Category for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Process	Transport	Energy of Material Resource (EMR)	NET
Tap best					
37	Credit for recycling (method 3)	0	0	0	0
	Production of reusable drinking container (32 oz PET, used 5 yrs)	0.0056	3.8E-04	0.0041	0.010
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	7.5E-04	5.0E-05	0.0010	0.0018
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	0.015	6.8E-06	1.6E-05	0.015
	Filling (reusable drinking container filled twice daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (once/wk, low water)	0.046	0	0	0.046
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	7.9E-05	6.7E-08	0	7.9E-05
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 100% recycling	-4.7E-05	8.3E-05	0	3.6E-05
	End of life management - caps & closures	-1.6E-05	1.4E-05	0	-1.8E-06
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**0.068**	**5.3E-04**	**0.0052**	**0.073**
	Percent by category	92%	1%	7%	100%
HOD ref					
38	Credit for recycling (method 1)	-0.14	-0.0031	-0.065	-0.21
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
	Production of HOD bottle (Polycarb, 40 uses)	0.37	0.0096	0.13	0.51
	Production of caps, closures	0.14	0.0076	0.16	0.30
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	0.60	1.7E-05	4.0E-05	0.60
	Filling (reusable drinking container filled once daily)	0.022	0	0	0.022
	Distribution of filled containers (50 mi dist, 75 mi route)	0	1.52	0	1.52
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	1.85	0	0	1.85
	Industrial washing of HOD container	0.14	3.6E-05	0	0.14
	Wastewater treatment	0.0086	7.3E-06	0	0.0086
	Chilling (HOD chiller unit)	2.00	0	0	2.00
	End of life management - HOD 100% recycling, container 0%	0.011	0.0023	0	0.014
	End of life management - caps & closures	-0.0025	0.0022	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**5.27**	**1.57**	**0.26**	**7.10**
	Percent by category	74%	22%	4%	100%
HOD PET					
39	Credit for recycling (method 1)	-0.057	-0.0027	-0.068	-0.13
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
	Production of HOD bottle (PET, 40 uses)	0.18	0.012	0.14	0.33
	Production of caps, closures	0.14	0.0076	0.16	0.30
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	0.60	1.7E-05	4.0E-05	0.60
	Filling (reusable drinking container filled once daily)	0.022	0	0	0.022
	Distribution of filled containers (50 mi dist, 75 mi route)	0	1.52	0	1.52
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	1.85	0	0	1.85
	Industrial washing of HOD container	0.14	3.6E-05	0	0.14
	Wastewater treatment	0.0086	7.3E-06	0	0.0086
	Chilling (HOD chiller unit)	2.00	0	0	2.00
	End of life management - HOD 100% recycling, container 0%	0.012	0.0023	0	0.014
	End of life management - caps & closures	-0.0025	0.0022	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**5.17**	**1.57**	**0.26**	**7.01**
	Percent by category	74%	22%	4%	100%
HOD heavy					
40	Credit for recycling (method 1)	-0.16	-0.0034	-0.072	-0.23
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
	Production of HOD bottle (Polycarb 10% heavier, 40 uses)	0.41	0.011	0.14	0.56
	Production of caps, closures	0.14	0.0076	0.16	0.30
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	0.60	1.7E-05	4.0E-05	0.60
	Filling (reusable drinking container filled once daily)	0.022	0	0	0.022
	Distribution of filled containers (50 mi dist, 75 mi route)	0	1.53	0	1.53
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	1.85	0	0	1.85
	Industrial washing of HOD container	0.14	3.6E-05	0	0.14
	Wastewater treatment	0.0086	7.3E-06	0	0.0086
	Chilling (HOD chiller unit)	2.00	0	0	2.00
	End of life management - HOD 100% recycling, container 0%	0.012	0.0024	0	0.015
	End of life management - caps & closures	-0.0025	0.0022	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**5.30**	**1.57**	**0.27**	**7.14**
	Percent by category	74%	22%	4%	100%

Table 2-10. Energy by Category for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Process	Transport	Energy of Material Resource (EMR)	NET
HOD 30 trip					
41	Credit for recycling (method 1)	-0.19	-0.0041	-0.087	-0.28
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
	Production of HOD bottle (Polycarb, 30 uses)	0.49	0.013	0.18	0.68
	Production of caps, closures	0.14	0.0076	0.16	0.30
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	0.60	1.7E-05	4.0E-05	0.60
	Filling (reusable drinking container filled once daily)	0.022	0	0	0.022
	Distribution of filled containers (50 mi dist, 75 mi route)	0	1.52	0	1.52
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	1.85	0	0	1.85
	Industrial washing of HOD container	0.14	3.6E-05	0	0.14
	Wastewater treatment	0.0086	7.3E-06	0	0.0086
	Chilling (HOD chiller unit)	2.00	0	0	2.00
	End of life management - HOD 100% recycling, container 0%	0.015	0.0027	0	0.018
	End of life management - caps & closures	-0.0025	0.0022	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**5.35**	**1.57**	**0.28**	**7.21**
	Percent by category	74%	22%	4%	100%
HOD nat					
42	Credit for recycling (method 1)	-0.14	-0.0031	-0.065	-0.21
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
	Production of HOD bottle (Polycarb, 40 uses)	0.37	0.0096	0.13	0.51
	Production of caps, closures	0.14	0.0076	0.16	0.30
	Production of secondary packaging	0	0	0	0
	Water processing (natural)	0.29	6.0E-06	1.4E-05	0.29
	Filling (reusable drinking container filled once daily)	0.022	0	0	0.022
	Distribution of filled containers (50 mi dist, 75 mi route)	0	1.52	0	1.52
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	1.85	0	0	1.85
	Industrial washing of HOD container	0.14	3.6E-05	0	0.14
	Wastewater treatment	0.0067	5.7E-06	0	0.0067
	Chilling (HOD chiller unit)	2.00	0	0	2.00
	End of life management - HOD 100% recycling, container 0%	0.011	0.0023	0	0.014
	End of life management - caps & closures	-0.0025	0.0022	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**4.97**	**1.57**	**0.26**	**6.80**
	Percent by category	73%	23%	4%	100%
HOD 200 mi distrib					
43	Credit for recycling (method 1)	-0.14	-0.0031	-0.065	-0.21
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
	Production of HOD bottle (Polycarb, 40 uses)	0.37	0.0096	0.13	0.51
	Production of caps, closures	0.14	0.0076	0.16	0.30
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	0.60	1.7E-05	4.0E-05	0.60
	Filling (reusable drinking container filled once daily)	0.022	0	0	0.022
	Distribution of filled containers (200 mi dist, 75 mi route)	0	2.61	0	2.61
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	1.85	0	0	1.85
	Industrial washing of HOD container	0.14	3.6E-05	0	0.14
	Wastewater treatment	0.0086	7.3E-06	0	0.0086
	Chilling (HOD chiller unit)	2.00	0	0	2.00
	End of life management - HOD 100% recycling, container 0%	0.011	0.0023	0	0.014
	End of life management - caps & closures	-0.0025	0.0022	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**5.27**	**2.65**	**0.26**	**8.19**
	Percent by category	64%	32%	3%	100%
HOD 50 mi route					
44	Credit for recycling (method 1)	-0.14	-0.0031	-0.065	-0.21
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
	Production of HOD bottle (Polycarb, 40 uses)	0.37	0.0096	0.13	0.51
	Production of caps, closures	0.14	0.0076	0.16	0.30
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	0.60	1.7E-05	4.0E-05	0.60
	Filling (reusable drinking container filled once daily)	0.022	0	0	0.022
	Distribution of filled containers (50 mi dist, 50 mi route)	0	1.13	0	1.13
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	1.85	0	0	1.85
	Industrial washing of HOD container	0.14	3.6E-05	0	0.14
	Wastewater treatment	0.0086	7.3E-06	0	0.0086
	Chilling (HOD chiller unit)	2.00	0	0	2.00
	End of life management - HOD 100% recycling, container 0%	0.011	0.0023	0	0.014
	End of life management - caps & closures	-0.0025	0.0022	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**5.27**	**1.18**	**0.26**	**6.72**
	Percent by category	79%	18%	4%	100%

Table 2-10. Energy by Category for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Process	Transport	Energy of Material Resource (EMR)	NET
HOD low chill					
45	Credit for recycling (method 1)	-0.14	-0.0031	-0.065	-0.21
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
	Production of HOD bottle (Polycarb, 40 uses)	0.37	0.0096	0.13	0.51
	Production of caps, closures	0.14	0.0076	0.16	0.30
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	0.60	1.7E-05	4.0E-05	0.60
	Filling (reusable drinking container filled once daily)	0.022	0	0	0.022
	Distribution of filled containers (50 mi dist, 75 mi route)	0	1.52	0	1.52
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	1.85	0	0	1.85
	Industrial washing of HOD container	0.14	3.6E-05	0	0.14
	Wastewater treatment	0.0086	7.3E-06	0	0.0086
	Chilling (faster consumption = shorter chilling)	1.33	0	0	1.33
	End of life management - HOD 100% recycling, container 0%	0.011	0.0023	0	0.014
	End of life management - caps & closures	-0.0025	0.0022	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**4.61**	**1.57**	**0.26**	**6.44**
	Percent by category	72%	24%	4%	100%
HOD high chill					
46	Credit for recycling (method 1)	-0.14	-0.0031	-0.065	-0.21
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.28	0.027	0.036	0.34
	Production of HOD bottle (Polycarb, 40 uses)	0.37	0.0096	0.13	0.51
	Production of caps, closures	0.14	0.0076	0.16	0.30
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	0.60	1.7E-05	4.0E-05	0.60
	Filling (reusable drinking container filled once daily)	0.022	0	0	0.022
	Distribution of filled containers (50 mi dist, 75 mi route)	0	1.52	0	1.52
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	1.85	0	0	1.85
	Industrial washing of HOD container	0.14	3.6E-05	0	0.14
	Wastewater treatment	0.0086	7.3E-06	0	0.0086
	Chilling (higher energy use)	2.40	0	0	2.40
	End of life management - HOD 100% recycling, container 0%	0.011	0.0023	0	0.014
	End of life management - caps & closures	-0.0025	0.0022	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**5.67**	**1.57**	**0.26**	**7.50**
	Percent by category	76%	21%	3%	100%
HOD best					
47	Credit for recycling (method 3)	-0.28	-0.0061	-0.13	-0.42
	Production of reusable drinking container (32 oz PET, used 5 yrs)	0.0056	3.8E-04	0.0041	0.010
	Production of HOD bottle (Polycarb, 40 uses)	0.37	0.0096	0.13	0.51
	Production of caps, closures	0.13	0.0071	0.15	0.29
	Production of secondary packaging	0	0	0	0
	Water processing (natural)	0.0015	6.6E-07	1.5E-06	0.0015
	Filling (reusable drinking container filled twice daily)	0.022	0	0	0.022
	Distribution of filled containers (50 mi dist, 50 mi route)	0	1.13	0	1.13
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (once/wk, low water use)	0.046	0	0	0.046
	Industrial washing of HOD container	0.14	3.6E-05	0	0.14
	Wastewater treatment	5.8E-04	4.9E-07	0	5.8E-04
	Chilling (faster consumption = shorter chilling)	1.33	0	0	1.33
	End of life management - HOD 100% recycling, container 100%	0.024	8.3E-05	0	0.024
	End of life management - caps & closures	-0.0023	0.0021	0	-2.5E-04
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**1.79**	**1.15**	**0.15**	**3.09**
	Percent by category	58%	37%	5%	100%
HOD worst					
48	Credit for recycling (method 1)	-0.084	-0.0040	-0.10	-0.19
	Production of reusable drinking container (16 oz drinking glass)	0.050	0.0017	0	0.052
	Production of HOD bottle (PET 10% heavier, 30 uses)	0.27	0.018	0.20	0.49
	Production of caps, closures	0.13	0.0071	0.15	0.28
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	0.62	2.5E-05	5.9E-05	0.62
	Filling (reusable drinking container filled once daily)	0.022	0	0	0.022
	Distribution of filled containers (200 mi dist, 100 mi route)	0	3.00	0	3.00
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (high water use, half full load)	4.64	0	0	4.64
	Industrial washing of HOD container	0.14	3.6E-05	0	0.14
	Wastewater treatment	0.018	1.5E-05	0	0.018
	Chilling (higher energy use)	2.40	0	0	2.40
	End of life management - HOD 100% recycling, container 0%	0.017	0.0030	0	0.020
	End of life management - caps & closures	-0.0023	0.0020	0	-2.5E-04
	End of life management - secondary packaging	0	0	0	0
	TOTAL	**8.21**	**3.03**	**0.25**	**11.5**
	Percent by category	71%	26%	2%	100%

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
PET ref R1											
1	Credit for recycling (method 1)	-0.88	-0.99	-0.34	-0.018	-0.0093	-0.049	-0.0017	-2.28	-0.032	-2.25
	Production of PET bottle	3.12	3.27	1.21	0.22	0.16	0	0.088	8.06	0.10	7.96
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.5E-04	0	6.7E-04	0.36	0	0.36
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0.045	0.21	0.094	-0.0024	0.026	0	0.0057	0.37	0	0.37
	End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
	End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
	TOTAL	**3.91**	**3.72**	**1.67**	**0.32**	**0.26**	**0.079**	**0.14**	**10.1**	**0.20**	**9.90**
	Percent by fuel	39%	37%	17%	3%	3%	1%	1%	100%		
PET ref R2											
2	Credit for recycling (method 2)	0	0	0	0	0	0	0	0	0	0
	Production of PET bottle	3.12	3.27	1.21	0.22	0.16	0	0.088	8.06	0.10	7.96
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.5E-04	0	6.7E-04	0.36	0	0.36
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	-0.0020	0.032	-0.012	-0.0040	-5.6E-04	0	-0.0011	0.012	0	0.012
	End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
	End of life management - secondary packaging	-0.0025	0.0068	-0.010	-0.0034	-4.7E-04	0	-9.1E-04	-0.010	0	-0.010
	TOTAL	**4.75**	**4.53**	**1.91**	**0.34**	**0.24**	**0.13**	**0.14**	**12.0**	**0.23**	**11.8**
	Percent by fuel	39%	38%	16%	3%	2%	1%	1%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
PET ref R3											
3	Credit for recycling (method 3)	-1.73	-1.95	-0.67	-0.036	-0.018	-0.097	-0.0034	-4.50	-0.062	-4.44
	Production of PET bottle	3.12	3.27	1.21	0.22	0.16	0	0.088	8.06	0.10	7.96
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.5E-04	0	6.7E-04	0.36	0	0.36
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0.095	0.33	0.22	0.0058	0.053	0	0.014	0.71	0	0.71
	End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
	End of life management - secondary packaging	-0.0021	0.013	-0.0097	-0.0034	-4.0E-04	0	-8.8E-04	-0.0030	0	-0.0030
	TOTAL	**3.11**	**2.89**	**1.47**	**0.31**	**0.28**	**0.030**	**0.15**	**8.24**	**0.17**	**8.07**
	Percent by fuel	38%	35%	18%	4%	3%	0%	2%	100%		
PET 1 liter											
4	Credit for recycling (method 1)	-1.27	-1.44	-0.44	-0.026	-0.0090	-0.024	-0.0012	-3.22	-0.046	-3.17
	Production of PET bottle (1 liter)	4.58	4.81	1.78	0.32	0.23	0	0.13	11.8	0.15	11.7
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.63	0.21	0.16	0.0067	0.037	0	0.010	1.05	0.074	0.98
	Production of secondary packaging	0.39	0.093	0.097	0.0023	0.013	0.064	0.0036	0.67	0.024	0.64
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.34	0.0074	0.0025	3.5E-04	0	6.7E-04	0.36	0	0.36
	Consumer transport (4% allocated to water)	0.010	0.22	0.0046	0.0016	2.2E-04	0	4.2E-04	0.24	0	0.24
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0.066	0.30	0.14	-0.0035	0.038	0	0.0084	0.55	0	0.55
	End of life management - caps & closures	-0.0012	0.0087	-0.0057	-0.0019	-2.7E-04	0	-5.1E-04	-9.5E-04	0	-9.5E-04
	End of life management - secondary packaging	-0.0018	0.0062	-0.0075	-0.0026	-3.4E-04	0	-6.9E-04	-0.0068	0	-0.0068
	TOTAL	**4.52**	**4.55**	**2.06**	**0.41**	**0.33**	**0.039**	**0.18**	**12.1**	**0.20**	**11.9**
	Percent by fuel	37%	38%	17%	3%	3%	0%	2%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
PET 8 oz											
5	Credit for recycling (method 1)	-1.72	-1.93	-0.67	-0.036	-0.019	-0.10	-0.0036	-4.49	-0.062	-4.43
	Production of PET bottle (8 oz)	6.09	6.39	2.36	0.42	0.31	0	0.17	15.7	0.20	15.5
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	1.33	0.45	0.33	0.014	0.077	0	0.022	2.23	0.16	2.07
	Production of secondary packaging	1.66	0.39	0.41	0.0097	0.053	0.27	0.015	2.81	0.10	2.71
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.34	0.0076	0.0026	3.6E-04	0	6.9E-04	0.37	0	0.37
	Consumer transport (4% allocated to water)	0.042	0.92	0.019	0.0066	9.1E-04	0	0.0017	0.99	0	0.99
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0.088	0.40	0.18	-0.0047	0.051	0	0.011	0.73	0	0.73
	End of life management - caps & closures	-0.0026	0.018	-0.012	-0.0041	-5.7E-04	0	-0.0011	-0.0020	0	-0.0020
	End of life management - secondary packaging	-0.0078	0.026	-0.032	-0.011	-0.0014	0	-0.0029	-0.029	0	-0.029
	TOTAL	**7.59**	**7.03**	**2.94**	**0.52**	**0.49**	**0.17**	**0.25**	**19.0**	**0.39**	**18.6**
	Percent by fuel	40%	37%	15%	3%	3%	1%	1%	100%		
PET light											
6	Credit for recycling (method 1)	-0.66	-0.73	-0.26	-0.014	-0.0082	-0.049	-0.0016	-1.72	-0.023	-1.70
	Production of PET bottle (lightweighted)	2.30	2.41	0.89	0.16	0.12	0	0.065	5.94	0.075	5.86
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.63	0.21	0.16	0.0067	0.037	0	0.010	1.05	0.074	0.98
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.4E-04	0	6.6E-04	0.36	0	0.36
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0.033	0.15	0.069	-0.0018	0.019	0	0.0042	0.28	0	0.28
	End of life management - caps & closures	-0.0012	0.0087	-0.0057	-0.0019	-2.7E-04	0	-5.1E-04	-9.5E-04	0	-9.5E-04
	End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
	TOTAL	**3.22**	**3.03**	**1.38**	**0.27**	**0.21**	**0.079**	**0.12**	**8.30**	**0.17**	**8.12**
	Percent by fuel	39%	37%	17%	3%	2%	1%	1%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
PET light, low mold											
7	Credit for recycling (method 1)	-0.66	-0.73	-0.26	-0.014	-0.0082	-0.049	-0.0016	-1.72	-0.023	-1.70
	Production of PET bottle (lightweight, lower molding energy)	2.29	2.41	0.85	0.15	0.11	0	0.061	5.86	0.075	5.79
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.63	0.21	0.16	0.0067	0.037	0	0.010	1.05	0.074	0.98
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.4E-04	0	6.6E-04	0.36	0	0.36
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0.033	0.15	0.069	-0.0018	0.019	0	0.0042	0.28	0	0.28
	End of life management - caps & closures	-0.0012	0.0087	-0.0057	-0.0019	-2.7E-04	0	-5.1E-04	-9.5E-04	0	-9.5E-04
	End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
	TOTAL	**3.20**	**3.03**	**1.34**	**0.26**	**0.20**	**0.079**	**0.11**	**8.22**	**0.17**	**8.05**
	Percent by fuel	39%	37%	16%	3%	2%	1%	1%	100%		
25% rPET R1											
8	Credit for recycling (method 1)	-0.77	-0.87	-0.30	-0.016	-0.0088	-0.049	-0.0017	-2.02	-0.028	-1.99
	Production of PET bottle (25% recycled content)	2.77	2.90	1.17	0.22	0.15	0	0.087	7.30	0.089	7.21
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.5E-04	0	6.7E-04	0.36	0	0.36
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0.045	0.20	0.097	-0.0015	0.026	0	0.0060	0.37	0	0.37
	End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
	End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
	TOTAL	**3.67**	**3.47**	**1.67**	**0.32**	**0.25**	**0.079**	**0.14**	**9.61**	**0.19**	**9.41**
	Percent by fuel	38%	36%	17%	3%	3%	1%	1%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems (million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
25% rPET R2											
9	Credit for recycling (method 2)	0	0	0	0	0	0	0	0	0	0
	Production of PET bottle (25% recycled content)	2.42	2.53	1.14	0.21	0.15	0	0.085	6.53	0.076	6.46
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.5E-04	0	6.7E-04	0.36	0	0.36
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	-0.0020	0.032	-0.012	-0.0040	-5.6E-04	0	-0.0011	0.012	0	0.012
	End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
	End of life management - secondary packaging	-0.0025	0.0068	-0.010	-0.0034	-4.7E-04	0	-9.1E-04	-0.010	0	-0.010
	TOTAL	**4.04**	**3.80**	**1.84**	**0.34**	**0.23**	**0.13**	**0.13**	**10.5**	**0.21**	**10.3**
	Percent by fuel	38%	36%	17%	3%	2%	1%	1%	100%		
25% rPET R3											
10	Credit for recycling (method 3)	-1.73	-1.95	-0.67	-0.036	-0.018	-0.097	-0.0034	-4.50	-0.062	-4.44
	Production of PET bottle (25% recycled content)	3.12	3.27	1.21	0.22	0.16	0	0.088	8.06	0.10	7.96
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.5E-04	0	6.7E-04	0.36	0	0.36
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0.095	0.33	0.22	0.0058	0.053	0	0.014	0.71	0	0.71
	End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
	End of life management - secondary packaging	-0.0021	0.013	-0.0097	-0.0034	-4.0E-04	0	-8.8E-04	-0.0030	0	-0.0030
	TOTAL	**3.11**	**2.89**	**1.47**	**0.31**	**0.28**	**0.030**	**0.15**	**8.24**	**0.17**	**8.07**
	Percent by fuel	38%	35%	18%	4%	3%	0%	2%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
PLA 0 decomp											
11	Credit for recycling (method 1)	-0.026	-0.011	-0.054	-8.9E-04	-0.0049	-0.049	-0.0014	-0.15	0	-0.15
	Production of PLA bottle	2.66	0.38	1.72	0.23	0.30	0	0.13	5.42	0	5.42
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.5E-04	0	6.7E-04	0.36	0	0.36
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 0% decomposition	-0.0034	0.086	-0.025	-0.0087	-0.0012	0	-0.0023	0.045	0	0.045
	End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
	End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
	TOTAL	**3.85**	**1.58**	**1.23**	**0.30**	**0.12**	**0.079**	**0.81**	**7.96**	**0.13**	**7.83**
	Percent by fuel	48%	20%	15%	4%	1%	1%	10%	100%		
PLA 100 decomp											
12	Credit for recycling (method 1)	-0.026	-0.011	-0.054	-8.9E-04	-0.0049	-0.049	-0.0014	-0.15	0	-0.15
	Production of PLA bottle	2.66	0.38	1.72	0.23	0.30	0	0.13	5.42	0	5.42
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.5E-04	0	6.7E-04	0.36	0	0.36
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 100% decomposition	-0.073	0.078	-0.27	-0.094	-0.013	0	-0.025	-0.40	0	-0.40
	End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
	End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
	TOTAL	**3.78**	**1.57**	**0.98**	**0.21**	**0.11**	**0.079**	**0.79**	**7.51**	**0.13**	**7.38**
	Percent by fuel	50%	21%	13%	3%	1%	1%	11%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
PLA compost											
13	Credit for recycling (method 1)	-0.026	-0.011	-0.054	-8.9E-04	-0.0049	-0.049	-0.0014	-0.15	0	-0.15
	Production of PLA bottle	2.66	0.38	1.72	0.23	0.30	0	0.13	5.42	0	5.42
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.5E-04	0	6.7E-04	0.36	0	0.36
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 100% composting	-0.0043	0.069	-0.026	-0.0088	-0.0012	0	-0.0023	0.027	0	0.027
	End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
	End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
	TOTAL	**3.85**	**1.56**	**1.23**	**0.30**	**0.12**	**0.079**	**0.81**	**7.94**	**0.13**	**7.81**
	Percent by fuel	48%	20%	15%	4%	1%	1%	10%	100%		
PET nat											
14	Credit for recycling (method 1)	-0.88	-0.99	-0.34	-0.018	-0.0093	-0.049	-0.0017	-2.28	-0.032	-2.25
	Production of PET bottle	3.12	3.27	1.21	0.22	0.16	0	0.088	8.06	0.10	7.96
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (natural)	0.044	0.0051	0.16	0.053	0.0074	0	0.014	0.28	0	0.28
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (130 mi)	0.041	0.87	0.019	0.0065	9.0E-04	0	0.0017	0.94	0	0.94
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	0	0	0	0	0	0	0	0	0	0
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0.045	0.21	0.094	-0.0024	0.026	0	0.0057	0.37	0	0.37
	End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
	End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
	TOTAL	**3.89**	**4.25**	**1.51**	**0.27**	**0.25**	**0.079**	**0.13**	**10.4**	**0.20**	**10.2**
	Percent by fuel	37%	41%	15%	3%	2%	1%	1%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
PET Maine nat											
15	Credit for recycling (method 1)	-0.88	-0.99	-0.34	-0.018	-0.0093	-0.049	-0.0017	-2.28	-0.032	-2.25
	Production of PET bottle	3.22	3.33	1.36	0.054	0.30	0	0.085	8.35	0.10	8.24
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (natural)	0.073	0.021	0.20	0.0084	0.046	0	0.013	0.36	0	0.36
	Filling	0.0059	0.0017	0.016	6.8E-04	0.0037	0	0.0011	0.029	0	0.029
	Distribution of filled containers from Maine	1.13	21.8	0.61	0.026	0.14	0	0.040	23.8	0	23.8
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	0	0	0	0	0	0	0	0	0	0
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0.045	0.21	0.094	-0.0024	0.026	0	0.0057	0.37	0	0.37
	End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
	End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
	TOTAL	**5.11**	**25.3**	**2.29**	**0.076**	**0.57**	**0.079**	**0.16**	**33.6**	**0.20**	**33.4**
	Percent by fuel	15%	75%	7%	0%	2%	0%	0%	100%		
PET Fiji nat											
16	Credit for recycling (method 1)	-1.79	-2.03	-0.64	-0.037	-0.014	-0.049	-0.0021	-4.57	-0.065	-4.50
	Production of PET bottle	6.67	6.88	2.81	0.11	0.62	0	0.17	17.3	0.21	17.0
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	1.17	0.40	0.29	0.012	0.068	0	0.019	1.96	0.14	1.82
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (natural)	1.1E-04	3.2E-05	2.9E-04	1.3E-05	6.9E-05	0	2.0E-05	5.3E-04	0	5.3E-04
	Filling	0.0059	0.0017	0.016	6.8E-04	0.0037	0	0.0011	0.029	0	0.029
	Distribution of filled containers from Fiji	0.66	12.7	0.35	0.015	0.082	0	0.023	13.9	0	13.9
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	0	0	0	0	0	0	0	0	0	0
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0.093	0.42	0.19	-0.0050	0.054	0	0.012	0.77	0	0.77
	End of life management - caps & closures	-0.0023	0.016	-0.011	-0.0036	-5.0E-04	0	-9.6E-04	-0.0018	0	-0.0018
	End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
	TOTAL	**7.60**	**19.1**	**3.20**	**0.097**	**0.83**	**0.079**	**0.23**	**31.1**	**0.33**	**30.8**
	Percent by fuel	24%	61%	10%	0%	3%	0%	1%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
PET Fiji free sea											
17	Credit for recycling (method 1)	-1.79	-2.03	-0.64	-0.037	-0.014	-0.049	-0.0021	-4.57	-0.065	-4.50
	Production of PET bottle	6.67	6.88	2.81	0.11	0.62	0	0.17	17.3	0.21	17.0
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	1.17	0.40	0.29	0.012	0.068	0	0.019	1.96	0.14	1.82
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (natural)	1.1E-04	3.2E-05	2.9E-04	1.3E-05	6.9E-05	0	2.0E-05	5.3E-04	0	5.3E-04
	Filling	0.0059	0.0017	0.016	6.8E-04	0.0037	0	0.0011	0.029	0	0.029
	Distribution of filled containers from Fiji (discounted ocean)	0.33	6.34	0.18	0.0075	0.041	0	0.012	6.90	0	6.90
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	0	0	0	0	0	0	0	0	0	0
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0.093	0.42	0.19	-0.0050	0.054	0	0.012	0.77	0	0.77
	End of life management - caps & closures	-0.0023	0.016	-0.011	-0.0036	-5.0E-04	0	-9.6E-04	-0.0018	0	-0.0018
	End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
	TOTAL	**7.27**	**12.7**	**3.02**	**0.090**	**0.79**	**0.079**	**0.22**	**24.1**	**0.33**	**23.8**
	Percent by fuel	30%	52%	13%	0%	3%	0%	1%	100%		
Glass France											
18	Credit for recycling (method 1)	-5.79	-1.59	-1.53	-0.050	-0.27	-0.068	-0.077	-9.38	0	-9.38
	Production of glass bottle	15.8	4.24	2.33	0.29	1.08	0	0.20	24.0	0	24.0
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	8.47	2.89	2.11	0.090	0.49	0	0.14	14.2	1.00	13.2
	Production of secondary packaging	1.10	0.26	0.27	0.0064	0.035	0.18	0.010	1.86	0.066	1.79
	Water processing (natural)	0.091	0.019	0.093	0.019	0.069	0	0.013	0.30	0	0.30
	Filling	0.0074	0.0016	0.0075	0.0015	0.0056	0	0.0011	0.025	0	0.025
	Distribution of filled containers from France	1.68	39.4	1.3E-04	0.38	0.52	0	0.064	42.1	0	42.1
	Consumer transport (4% allocated to water)	0.028	0.61	0.013	0.0044	6.1E-04	0	0.0012	0.66	0	0.66
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	0	0	0	0	0	0	0	0	0	0
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 74% recycling	0.18	0.63	0.41	0.020	0.095	0	0.027	1.35	0	1.35
	End of life management - caps & closures	-0.016	0.12	-0.076	-0.026	-0.0036	0	-0.0069	-0.013	0	-0.013
	End of life management - secondary packaging	-0.0051	0.017	-0.021	-0.0073	-9.6E-04	0	-0.0019	-0.019	0	-0.019
	TOTAL	**21.6**	**46.6**	**3.60**	**0.73**	**2.01**	**0.11**	**0.37**	**75.0**	**1.07**	**74.0**
	Percent by fuel	29%	62%	5%	1%	3%	0%	0%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
PET 500 mi empty											
19	Credit for recycling (method 1)	-0.88	-0.99	-0.34	-0.018	-0.0093	-0.049	-0.0017	-2.28	-0.032	-2.25
	Production of PET bottle (molded offsite)	3.16	4.03	1.23	0.22	0.16	0	0.090	8.88	0.10	8.78
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.5E-04	0	6.7E-04	0.36	0	0.36
	Consumer transport (4% allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0.045	0.21	0.094	-0.0024	0.026	0	0.0057	0.37	0	0.37
	End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
	End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
	TOTAL	**3.95**	**4.48**	**1.69**	**0.32**	**0.26**	**0.079**	**0.14**	**10.9**	**0.20**	**10.7**
	Percent by fuel	36%	41%	15%	3%	2%	1%	1%	100%		
PET 100% store trip											
20	Credit for recycling (method 1)	-0.88	-0.99	-0.34	-0.018	-0.0093	-0.049	-0.0017	-2.28	-0.032	-2.25
	Production of PET bottle	3.12	3.27	1.21	0.22	0.16	0	0.088	8.06	0.10	7.96
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.5E-04	0	6.7E-04	0.36	0	0.36
	Consumer transport (100% of trip allocated to water)	0.49	10.9	0.23	0.078	0.011	0	0.021	11.7	0	11.7
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0.045	0.21	0.094	-0.0024	0.026	0	0.0057	0.37	0	0.37
	End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
	End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
	TOTAL	**4.38**	**14.2**	**1.89**	**0.40**	**0.27**	**0.079**	**0.16**	**21.3**	**0.20**	**21.1**
	Percent by fuel	21%	66%	9%	2%	1%	0%	1%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
PET refrig											
21	Credit for recycling (method 1)	-0.88	-0.99	-0.34	-0.018	-0.0093	-0.049	-0.0017	-2.28	-0.032	-2.25
	Production of PET bottle	3.12	3.27	1.21	0.22	0.16	0	0.088	8.06	0.10	7.96
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.5E-04	0	6.7E-04	0.36	0	0.36
	Consumer transport (4% of trip allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (3.5 days home refrig)	0.051	0.0059	0.18	0.062	0.0086	0	0.016	0.33	0	0.33
	End of life management - bottles @ 62% recycling	0.045	0.21	0.094	-0.0024	0.026	0	0.0057	0.37	0	0.37
	End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
	End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
	TOTAL	**3.96**	**3.73**	**1.85**	**0.38**	**0.27**	**0.079**	**0.16**	**10.4**	**0.20**	**10.2**
	Percent by fuel	38%	36%	18%	4%	3%	1%	2%	100%		
PET 37%R											
22	Credit for recycling (method 1)	-0.54	-0.59	-0.22	-0.011	-0.0075	-0.049	-0.0016	-1.42	-0.019	-1.40
	Production of PET bottle	3.12	3.27	1.21	0.22	0.16	0	0.088	8.06	0.10	7.96
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.72	0.25	0.18	0.0076	0.042	0	0.012	1.20	0.085	1.12
	Production of secondary packaging	0.78	0.19	0.19	0.0046	0.025	0.13	0.0071	1.33	0.047	1.28
	Water processing (purified municipal)	0.092	0.011	0.32	0.11	0.015	0	0.029	0.58	0	0.58
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi)	0.016	0.33	0.0073	0.0025	3.5E-04	0	6.7E-04	0.36	0	0.36
	Consumer transport (4% of trip allocated to water)	0.020	0.44	0.0091	0.0031	4.3E-04	0	8.3E-04	0.47	0	0.47
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.3E-04	5.2E-05	0.0011	3.3E-04	4.5E-05	0	8.7E-05	0.0019	0	0.0019
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 37% recycling	0.025	0.16	0.044	-0.0057	0.015	0	0.0023	0.24	0	0.24
	End of life management - caps & closures	-0.0014	0.0099	-0.0065	-0.0022	-3.1E-04	0	-5.9E-04	-0.0011	0	-0.0011
	End of life management - secondary packaging	-0.0037	0.012	-0.015	-0.0052	-6.8E-04	0	-0.0014	-0.014	0	-0.014
	TOTAL	**4.24**	**4.07**	**1.73**	**0.33**	**0.25**	**0.079**	**0.14**	**10.8**	**0.21**	**10.6**
	Percent by fuel	39%	38%	16%	3%	2%	1%	1%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
PET best											
23	Credit for recycling (method 3)	-2.00	-2.29	-0.66	-0.041	-0.010	0	-7.7E-04	-5.00	-0.074	-4.93
	Production of PET bottle (lightweight, 25% recycl cont)	2.29	2.41	0.85	0.15	0.11	0	0.061	5.86	0.075	5.79
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.63	0.21	0.16	0.0067	0.037	0	0.010	1.05	0.074	0.98
	Production of secondary packaging (film only)	0.74	0.16	0.054	0.0023	0.013	0	0.0036	0.97	0.049	0.92
	Water processing (natural)	6.5E-05	7.6E-06	2.3E-04	8.0E-05	1.1E-05	0	2.1E-05	4.2E-04	0	4.2E-04
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (20 mi)	0.0063	0.13	0.0029	0.0010	1.4E-04	0	2.6E-04	0.14	0	0.14
	Consumer transport (0% of trip allocated to water)	1.3E-04	0.0029	6.1E-05	2.1E-05	2.9E-06	0	5.6E-06	0.0032	0	0.0032
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	0	0	0	0	0	0	0	0	0	0
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 100% recycling	0.11	0.35	0.27	0.012	0.064	0	0.018	0.83	0	0.83
	End of life management - caps & closures	-0.0012	0.0087	-0.0057	-0.0019	-2.7E-04	0	-5.1E-04	-9.5E-04	0	-9.5E-04
	End of life management - secondary packaging	-0.0017	0.0055	-0.0069	-0.0024	-3.3E-04	0	-6.3E-04	-0.0064	0	-0.0064
	TOTAL	**1.78**	**1.00**	**0.67**	**0.13**	**0.22**	**0**	**0.093**	**3.89**	**0.12**	**3.76**
	Percent by fuel	46%	26%	17%	3%	6%	0%	2%	100%		
PET worst											
24	Credit for recycling (method 1)	-0.060	-0.025	-0.13	-0.0021	-0.011	-0.11	-0.0032	-0.34	0	-0.34
	Production of PET bottle (8 oz, molded off-site)	6.34	7.26	2.67	0.11	0.59	0	0.17	17.1	0.20	16.9
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	1.33	0.45	0.33	0.014	0.077	0	0.022	2.23	0.16	2.07
	Production of secondary packaging	1.81	0.43	0.45	0.011	0.058	0.29	0.017	3.07	0.11	2.96
	Water processing (natural)	0.081	0.023	0.22	0.0093	0.051	0	0.015	0.40	0	0.40
	Filling	0.0059	0.0017	0.016	6.8E-04	0.0037	0	0.0011	0.029	0	0.029
	Distribution of filled containers from Maine	1.17	22.6	0.63	0.027	0.15	0	0.042	24.6	0	24.6
	Consumer transport (100% of trip allocated to water)	1.04	23.0	0.48	0.16	0.023	0	0.044	24.7	0	24.7
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	1.3E-05	2.1E-06	4.3E-05	1.3E-05	1.8E-06	0	3.5E-06	7.6E-05	0	7.6E-05
	Chilling (1 wk home refrig)	0.21	0.025	0.77	0.26	0.036	0	0.070	1.37	0	1.37
	End of life management - bottles @ 0% recycling	-0.010	0.16	-0.061	-0.021	-0.0029	0	-0.0055	0.062	0	0.062
	End of life management - caps & closures	-0.0026	0.018	-0.012	-0.0041	-5.7E-04	0	-0.0011	-0.0020	0	-0.0020
	End of life management - secondary packaging	-0.0085	0.029	-0.035	-0.012	-0.0016	0	-0.0032	-0.031	0	-0.031
	TOTAL	**11.9**	**54.0**	**5.33**	**0.56**	**0.97**	**0.18**	**0.36**	**73.3**	**0.46**	**72.8**
	Percent by fuel	16%	74%	7%	1%	1%	0%	0%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems (million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
PLA best											
25	Credit for recycling (method 3)	0	0	0	0	0	0	0	0	0	0
	Production of PLA bottle	1.95	0.28	1.23	0.16	0.22	0	0.089	3.92	0	3.92
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.63	0.21	0.16	0.0067	0.037	0	0.010	1.05	0.074	0.98
	Production of secondary packaging (film only)	0.74	0.16	0.054	0.0023	0.013	0	0.0036	0.97	0.049	0.92
	Water processing (natural)	6.5E-05	7.6E-06	2.3E-04	8.0E-05	1.1E-05	0	2.1E-05	4.2E-04	0	4.2E-04
	Filling	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (20 mi)	0.0063	0.13	0.0029	0.0010	1.4E-04	0	2.6E-04	0.14	0	0.14
	Consumer transport (0% of trip allocated to water)	1.3E-04	0.0029	6.1E-05	2.1E-05	2.9E-06	0	5.6E-06	0.0032	0	0.0032
	Home washing of reusable drinking container	0	0	0	0	0	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	0	0	0	0	0	0	0	0	0	0
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - bottles @ 0% decomposition	-0.0025	0.063	-0.019	-0.0064	-8.8E-04	0	-0.0017	0.033	0	0.033
	End of life management - caps & closures	-0.0012	0.0087	-0.0057	-0.0019	-2.7E-04	0	-5.1E-04	-9.5E-04	0	-9.5E-04
	End of life management - secondary packaging	-0.0017	0.0055	-0.0069	-0.0024	-3.3E-04	0	-6.3E-04	-0.0064	0	-0.0064
	TOTAL	**3.01**	**0.78**	**0.60**	**0.12**	**0.076**	**0**	**0.57**	**5.17**	**0.12**	**5.04**
	Percent by fuel	58%	15%	12%	2%	1%	0%	11%	100%		
Tap Al ref											
26	Credit for recycling (method 1)	0	0	0	0	0	0	0	0	0	0
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.013	0.0044	0.0032	1.4E-04	7.6E-04	0	2.1E-04	0.022	0.0015	0.020
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (tap)	0.0052	5.4E-04	0.015	0.0050	7.5E-04	0	0.0013	0.028	0	0.028
	Filling (reusable drinking container filled once daily)	0	0	0	0	0	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0	0	0	0	0	0
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.56	0.029	0.85	0.29	0.040	0	0.077	1.85	0	1.85
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	0.0011	1.7E-04	0.0035	0.0011	1.5E-04	0	2.8E-04	0.0062	0	0.0062
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	6.1E-05	0.0012	2.7E-05	9.3E-06	1.3E-06	0	2.5E-06	0.0013	0	0.0013
	End of life management - caps & closures	-2.5E-05	1.8E-04	-1.2E-04	-4.0E-05	-5.5E-06	0	-1.1E-05	-2.0E-05	0	-2.0E-05
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**0.65**	**0.12**	**0.98**	**0.36**	**0.066**	**0**	**0.085**	**2.25**	**0.0015**	**2.25**
	Percent by fuel	29%	5%	43%	16%	3%	0%	4%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
Tap PET											
27	Credit for recycling (method 1)	0	0	0	0	0	0	0	0	0	0
	Production of reusable drinking container (32 oz PET, 1 yr use)	0.038	0.039	0.019	7.6E-04	0.0042	0	0.0012	0.10	0.0012	0.10
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.012	0.0040	0.0029	1.2E-04	6.8E-04	0	1.9E-04	0.020	0.0014	0.018
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (tap)	0.0043	4.5E-04	0.012	0.0042	6.2E-04	0	0.0011	0.023	0	0.023
	Filling (reusable drinking container filled once daily)	0	0	0	0	0	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0	0	0	0	0	0
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.35	0.018	0.53	0.18	0.025	0	0.048	1.16	0	1.16
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	6.7E-04	1.1E-04	0.0022	6.7E-04	9.2E-05	0	1.8E-04	0.0039	0	0.0039
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	-5.8E-05	9.4E-04	-3.5E-04	-1.2E-04	-1.7E-05	0	-3.2E-05	3.6E-04	0	3.6E-04
	End of life management - caps & closures	-2.3E-05	1.6E-04	-1.1E-04	-3.6E-05	-5.0E-06	0	-9.6E-06	-1.8E-05	0	-1.8E-05
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**0.41**	**0.063**	**0.57**	**0.19**	**0.031**	**0**	**0.051**	**1.31**	**0.0025**	**1.31**
	Percent by fuel	31%	5%	43%	14%	2%	0%	4%	100%		
Tap steel											
28	Credit for recycling (method 1)	0	0	0	0	0	0	0	0	0	0
	Production of reusable drinking container (27 oz steel, 1 yr use)	0.011	0.026	0.085	0.0033	8.5E-04	0	6.4E-05	0.13	0	0.13
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.028	0.0097	0.0071	3.0E-04	0.0017	0	4.7E-04	0.048	0.0034	0.044
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (tap)	0.0046	4.8E-04	0.013	0.0044	6.6E-04	0	0.0012	0.025	0	0.025
	Filling (reusable drinking container filled once daily)	0	0	0	0	0	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0	0	0	0	0	0
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.42	0.022	0.63	0.22	0.030	0	0.057	1.37	0	1.37
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	8.0E-04	1.3E-04	0.0026	7.9E-04	1.1E-04	0	2.1E-04	0.0046	0	0.0046
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	7.8E-05	0.0016	3.5E-05	1.2E-05	1.7E-06	0	3.2E-06	0.0017	0	0.0017
	End of life management - caps & closures	-5.5E-05	3.9E-04	-2.6E-04	-8.8E-05	-1.2E-05	0	-2.3E-05	-4.3E-05	0	-4.3E-05
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**0.46**	**0.059**	**0.74**	**0.23**	**0.033**	**0**	**0.059**	**1.58**	**0.0034**	**1.57**
	Percent by fuel	29%	4%	47%	14%	2%	0%	4%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems (million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
Tap glass											
29	Credit for recycling (method 1)	0	0	0	0	0	0	0	0	0	0
	Production of reusable drinking container (16 oz drinking glass, 1 yr use)	0.033	0.0090	0.0083	2.7E-04	0.0015	0	4.3E-04	0.052	0	0.052
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0	0	0	0	0	0	0	0	0	0
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (tap)	0.0058	6.0E-04	0.017	0.0056	8.3E-04	0	0.0015	0.031	0	0.031
	Filling (reusable drinking container filled once daily)	0	0	0	0	0	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0	0	0	0	0	0
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.70	0.036	1.07	0.37	0.050	0	0.097	2.32	0	2.32
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	0.0013	2.1E-04	0.0043	0.0013	1.8E-04	0	3.5E-04	0.0078	0	0.0078
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	5.1E-05	0.0011	2.3E-05	8.0E-06	1.1E-06	0	2.1E-06	0.0011	0	0.0011
	End of life management - caps & closures	0	0	0	0	0	0	0	0	0	0
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**0.74**	**0.047**	**1.10**	**0.37**	**0.053**	**0**	**0.099**	**2.41**	**0**	**2.41**
	Percent by fuel	31%	2%	45%	15%	2%	0%	4%	100%		
Tap Al 5 yr											
30	Credit for recycling (method 1)	0	0	0	0	0	0	0	0	0	0
	Production of reusable drinking container (20 oz aluminum, 5 yrs use)	0.014	0.016	0.021	0.012	0.0047	0	0.0011	0.068	0	0.068
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.0026	8.9E-04	6.5E-04	2.8E-05	1.5E-04	0	4.3E-05	0.0044	3.1E-04	0.0040
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (tap)	0.0052	5.4E-04	0.015	0.0050	7.5E-04	0	0.0013	0.028	0	0.028
	Filling (reusable drinking container filled once daily)	0	0	0	0	0	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0	0	0	0	0	0
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.56	0.029	0.85	0.29	0.040	0	0.077	1.85	0	1.85
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	0.0011	1.7E-04	0.0035	0.0011	1.5E-04	0	2.8E-04	0.0062	0	0.0062
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	1.2E-05	2.5E-04	5.4E-06	1.9E-06	2.6E-07	0	4.9E-07	2.7E-04	0	2.7E-04
	End of life management - caps & closures	-5.0E-06	3.6E-05	-2.3E-05	-8.0E-06	-1.1E-06	0	-2.1E-06	-3.9E-06	0	-3.9E-06
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**0.59**	**0.047**	**0.89**	**0.31**	**0.046**	**0**	**0.080**	**1.96**	**3.1E-04**	**1.96**
	Percent by fuel	30%	2%	46%	16%	2%	0%	4%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
Tap Al 100%R											
31	Credit for recycling (method 1)	-0.034	-0.033	-0.053	-0.030	-0.0066	0	-0.0027	-0.16	0	-0.16
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.013	0.0044	0.0032	1.4E-04	7.6E-04	0	2.1E-04	0.022	0.0015	0.020
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (tap)	0.0052	5.4E-04	0.015	0.0050	7.5E-04	0	0.0013	0.028	0	0.028
	Filling (reusable drinking container filled once daily)	0	0	0	0	0	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0	0	0	0	0	0
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.56	0.029	0.85	0.29	0.040	0	0.077	1.85	0	1.85
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	0.0011	1.7E-04	0.0035	0.0011	1.5E-04	0	2.8E-04	0.0062	0	0.0062
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - drinking containers @ 100% recycling	0.0090	0.0030	0.0035	1.6E-04	8.3E-04	0	2.4E-04	0.017	0	0.017
	End of life management - caps & closures	-2.5E-05	1.8E-04	-1.2E-04	-4.0E-05	-5.5E-06	0	-1.1E-05	-2.0E-05	0	-2.0E-05
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**0.63**	**0.084**	**0.93**	**0.33**	**0.060**	**0**	**0.082**	**2.11**	**0.0015**	**2.11**
	Percent by fuel	30%	4%	44%	16%	3%	0%	4%	100%		
Tap Al 2x fill											
32	Credit for recycling (method 1)	0	0	0	0	0	0	0	0	0	0
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.035	0.040	0.052	0.030	0.012	0	0.0028	0.17	0	0.17
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.0065	0.0022	0.0016	6.9E-05	3.8E-04	0	1.1E-04	0.011	7.7E-04	0.010
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (tap)	0.0040	4.2E-04	0.012	0.0039	5.8E-04	0	0.0010	0.022	0	0.022
	Filling (reusable drinking container filled twice daily)	0	0	0	0	0	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0	0	0	0	0	0
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.28	0.015	0.43	0.15	0.020	0	0.039	0.93	0	0.93
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	5.4E-04	8.5E-05	0.0017	5.4E-04	7.4E-05	0	1.4E-04	0.0031	0	0.0031
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	3.0E-05	6.2E-04	1.4E-05	4.7E-06	6.4E-07	0	1.2E-06	6.7E-04	0	6.7E-04
	End of life management - caps & closures	-1.3E-05	8.9E-05	-5.9E-05	-2.0E-05	-2.8E-06	0	-5.3E-06	-9.8E-06	0	-9.8E-06
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**0.33**	**0.058**	**0.49**	**0.18**	**0.033**	**0**	**0.043**	**1.13**	**7.7E-04**	**1.13**
	Percent by fuel	29%	5%	43%	16%	3%	0%	4%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
Tap Al wk wash											
33	Credit for recycling (method 1)	0	0	0	0	0	0	0	0	0	0
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.013	0.0044	0.0032	1.4E-04	7.6E-04	0	2.1E-04	0.022	0.0015	0.020
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (tap)	0.0032	3.3E-04	0.0092	0.0031	4.6E-04	0	8.3E-04	0.017	0	0.017
	Filling (reusable drinking container filled once daily)	0	0	0	0	0	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0	0	0	0	0	0
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (once/week, high water use)	0.080	0.0042	0.12	0.042	0.0058	0	0.011	0.26	0	0.26
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	1.5E-04	2.4E-05	4.9E-04	1.5E-04	2.1E-05	0	4.0E-05	8.9E-04	0	8.9E-04
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	6.1E-05	0.0012	2.7E-05	9.3E-06	1.3E-06	0	2.5E-06	0.0013	0	0.0013
	End of life management - caps & closures	-2.5E-05	1.8E-04	-1.2E-04	-4.0E-05	-5.5E-06	0	-1.1E-05	-2.0E-05	0	-2.0E-05
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**0.17**	**0.090**	**0.24**	**0.10**	**0.031**	**0**	**0.018**	**0.65**	**0.0015**	**0.65**
	Percent by fuel	26%	14%	37%	16%	5%	0%	3%	100%		
Tap Al low wash											
34	Credit for recycling (method 1)	0	0	0	0	0	0	0	0	0	0
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.013	0.0044	0.0032	1.4E-04	7.6E-04	0	2.1E-04	0.022	0.0015	0.020
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (tap)	0.0035	3.7E-04	0.010	0.0034	5.1E-04	0	9.1E-04	0.019	0	0.019
	Filling (reusable drinking container filled once daily)	0	0	0	0	0	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0	0	0	0	0	0
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, low water use)	0.24	0.017	0.52	0.18	0.025	0	0.047	1.03	0	1.03
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	3.1E-04	4.9E-05	0.0010	3.1E-04	4.2E-05	0	8.1E-05	0.0018	0	0.0018
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	6.1E-05	0.0012	2.7E-05	9.3E-06	1.3E-06	0	2.5E-06	0.0013	0	0.0013
	End of life management - caps & closures	-2.5E-05	1.8E-04	-1.2E-04	-4.0E-05	-5.5E-06	0	-1.1E-05	-2.0E-05	0	-2.0E-05
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**0.32**	**0.10**	**0.64**	**0.24**	**0.050**	**0**	**0.054**	**1.41**	**0.0015**	**1.41**
	Percent by fuel	23%	7%	45%	17%	4%	0%	4%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
Tap Al 1/2 full wash											
35	Credit for recycling (method 1)	0	0	0	0	0	0	0	0	0	0
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.013	0.0044	0.0032	1.4E-04	7.6E-04	0	2.1E-04	0.022	0.0015	0.020
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (tap)	0.0075	7.8E-04	0.022	0.0073	0.0011	0	0.0019	0.040	0	0.040
	Filling (reusable drinking container filled once daily)	0	0	0	0	0	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0	0	0	0	0	0
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (high water, half full load)	1.12	0.058	1.71	0.58	0.081	0	0.15	3.71	0	3.71
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	0.0021	3.4E-04	0.0069	0.0021	3.0E-04	0	5.7E-04	0.012	0	0.012
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	6.1E-05	0.0012	2.7E-05	9.3E-06	1.3E-06	0	2.5E-06	0.0013	0	0.0013
	End of life management - caps & closures	-2.5E-05	1.8E-04	-1.2E-04	-4.0E-05	-5.5E-06	0	-1.1E-05	-2.0E-05	0	-2.0E-05
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**1.22**	**0.14**	**1.84**	**0.65**	**0.11**	**0**	**0.16**	**4.13**	**0.0015**	**4.12**
	Percent by fuel	29%	4%	45%	16%	3%	0%	4%	100%		
Tap Al ice											
36	Credit for recycling (method 1)	0	0	0	0	0	0	0	0	0	0
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.013	0.0044	0.0032	1.4E-04	7.6E-04	0	2.1E-04	0.022	0.0015	0.020
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (tap)	0.0066	6.9E-04	0.019	0.0064	9.5E-04	0	0.0017	0.035	0	0.035
	Filling (reusable drinking container filled once daily)	0	0	0	0	0	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0	0	0	0	0	0
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.56	0.029	0.85	0.29	0.040	0	0.077	1.85	0	1.85
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	0.0011	1.7E-04	0.0035	0.0011	1.5E-04	0	2.8E-04	0.0062	0	0.0062
	Chilling (50% ice)	0	0	0	0	0	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	6.1E-05	0.0012	2.7E-05	9.3E-06	1.3E-06	0	2.5E-06	0.0013	0	0.0013
	End of life management - caps & closures	-2.5E-05	1.8E-04	-1.2E-04	-4.0E-05	-5.5E-06	0	-1.1E-05	-2.0E-05	0	-2.0E-05
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**0.65**	**0.12**	**0.98**	**0.36**	**0.066**	**0**	**0.085**	**2.26**	**0.0015**	**2.26**
	Percent by fuel	29%	5%	43%	16%	3%	0%	4%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
Tap best											
37	Credit for recycling (method 3)	0	0	0	0	0	0	0	0	0	0
	Production of reusable drinking container (32 oz PET, used 5 yrs)	0.0038	0.0039	0.0019	7.6E-05	4.2E-04	0	1.2E-04	0.010	1.2E-04	0.010
	Production of HOD bottle	0	0	0	0	0	0	0	0	0	0
	Production of caps, closures	0.0012	4.0E-04	2.9E-04	1.2E-05	6.8E-05	0	1.9E-05	0.0020	1.4E-04	0.0018
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (tap)	0.0029	3.0E-04	0.0083	0.0028	4.2E-04	0	7.5E-04	0.015	0	0.015
	Filling (reusable drinking container filled twice daily)	0	0	0	0	0	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0	0	0	0	0	0
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (once/wk, low water)	0.011	7.8E-04	0.023	0.0080	0.0011	0	0.0021	0.046	0	0.046
	Industrial washing of HOD container	0	0	0	0	0	0	0	0	0	0
	Wastewater treatment	1.4E-05	2.2E-06	4.4E-05	1.4E-05	1.9E-06	0	3.6E-06	7.9E-05	0	7.9E-05
	Chilling (none)	0	0	0	0	0	0	0	0	0	0
	End of life management - drinking containers @ 100% recycling	-5.8E-06	9.4E-05	-3.5E-05	-1.2E-05	-1.7E-06	0	-3.2E-06	3.6E-05	0	3.6E-05
	End of life management - caps & closures	-2.3E-06	1.6E-05	-1.1E-05	-3.6E-06	-5.0E-07	0	-9.6E-07	-1.8E-06	0	-1.8E-06
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**0.019**	**0.0055**	**0.034**	**0.011**	**0.0020**	**0**	**0.0030**	**0.074**	**2.5E-04**	**0.073**
	Percent by fuel	25%	7%	46%	15%	3%	0%	4%	100%		
HOD ref											
38	Credit for recycling (method 1)	-0.13	-0.044	-0.030	-6.3E-04	-0.0035	0	-9.9E-04	-0.21	0	-0.21
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
	Production of HOD bottle (Polycarb, 40 uses)	0.28	0.096	0.11	0.0033	0.018	0	0.0051	0.51	0	0.51
	Production of caps, closures	0.21	0.049	0.045	0.0019	0.010	0	0.0030	0.32	0.014	0.30
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (purified municipal)	0.094	0.011	0.33	0.11	0.016	0	0.030	0.60	0	0.60
	Filling (reusable drinking container filled once daily)	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi dist, 75 mi route)	0.067	1.41	0.031	0.011	0.0015	0	0.0028	1.52	0	1.52
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.56	0.029	0.85	0.29	0.040	0	0.077	1.85	0	1.85
	Industrial washing of HOD container	0.024	0.0033	0.075	0.023	0.0053	0	0.0066	0.14	0	0.14
	Wastewater treatment	0.0015	2.4E-04	0.0048	0.0015	2.1E-04	0	3.9E-04	0.0086	0	0.0086
	Chilling (HOD chiller unit)	0.31	0.037	1.11	0.38	0.053	0	0.10	2.00	0	2.00
	End of life management - HOD 100% recycling, container 0%	0.0023	0.0035	0.0058	-2.1E-05	0.0015	0	3.6E-04	0.014	0	0.014
	End of life management - caps & closures	-3.5E-04	0.0025	-0.0016	-5.5E-04	-7.6E-05	0	-1.5E-04	-2.7E-04	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**1.50**	**1.68**	**2.65**	**0.89**	**0.17**	**0**	**0.23**	**7.12**	**0.014**	**7.10**
	Percent by fuel	21%	24%	37%	13%	2%	0%	3%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
HOD PET											
39	Credit for recycling (method 1)	-0.055	-0.059	-0.012	-4.4E-04	-0.0024	0	-6.9E-04	-0.13	-0.0019	-0.13
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
	Production of HOD bottle (PET, 40 uses)	0.12	0.13	0.062	0.0025	0.014	0	0.0039	0.34	0.0038	0.33
	Production of caps, closures	0.21	0.049	0.045	0.0019	0.010	0	0.0030	0.32	0.014	0.30
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (purified municipal)	0.094	0.011	0.33	0.11	0.016	0	0.030	0.60	0	0.60
	Filling (reusable drinking container filled once daily)	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi dist, 75 mi route)	0.067	1.41	0.031	0.011	0.0015	0	0.0028	1.52	0	1.52
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.56	0.029	0.85	0.29	0.040	0	0.077	1.85	0	1.85
	Industrial washing of HOD container	0.024	0.0033	0.075	0.023	0.0053	0	0.0066	0.14	0	0.14
	Wastewater treatment	0.0015	2.4E-04	0.0048	0.0015	2.1E-04	0	3.9E-04	0.0086	0	0.0086
	Chilling (HOD chiller unit)	0.31	0.037	1.11	0.38	0.053	0	0.10	2.00	0	2.00
	End of life management - HOD 100% recycling, container 0%	0.0024	0.0035	0.0061	9.7E-05	0.0015	0	4.0E-04	0.014	0	0.014
	End of life management - caps & closures	-3.5E-04	0.0025	-0.0016	-5.5E-04	-7.6E-05	0	-1.5E-04	-2.7E-04	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**1.42**	**1.69**	**2.63**	**0.89**	**0.16**	**0**	**0.23**	**7.02**	**0.016**	**7.01**
	Percent by fuel	20%	24%	37%	13%	2%	0%	3%	100%		
HOD heavy											
40	Credit for recycling (method 1)	-0.14	-0.048	-0.033	-7.0E-04	-0.0038	0	-0.0011	-0.23	0	-0.23
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
	Production of HOD bottle (Polycarb 10% heavier, 40 uses)	0.31	0.11	0.12	0.0036	0.020	0	0.0056	0.56	0	0.56
	Production of caps, closures	0.21	0.049	0.045	0.0019	0.010	0	0.0030	0.32	0.014	0.30
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (purified municipal)	0.094	0.011	0.33	0.11	0.016	0	0.030	0.60	0	0.60
	Filling (reusable drinking container filled once daily)	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi dist, 75 mi route)	0.067	1.41	0.031	0.011	0.0015	0	0.0028	1.53	0	1.53
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.56	0.029	0.85	0.29	0.040	0	0.077	1.85	0	1.85
	Industrial washing of HOD container	0.024	0.0033	0.075	0.023	0.0053	0	0.0066	0.14	0	0.14
	Wastewater treatment	0.0015	2.4E-04	0.0048	0.0015	2.1E-04	0	3.9E-04	0.0086	0	0.0086
	Chilling (HOD chiller unit)	0.31	0.037	1.11	0.38	0.053	0	0.10	2.00	0	2.00
	End of life management - HOD 100% recycling, container 0%	0.0026	0.0037	0.0064	-2.4E-05	0.0017	0	4.0E-04	0.015	0	0.015
	End of life management - caps & closures	-3.5E-04	0.0025	-0.0016	-5.5E-04	-7.6E-05	0	-1.5E-04	-2.7E-04	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**1.51**	**1.69**	**2.66**	**0.89**	**0.17**	**0**	**0.23**	**7.15**	**0.014**	**7.14**
	Percent by fuel	21%	24%	37%	12%	2%	0%	3%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
HOD 30 trip											
41	Credit for recycling (method 1)	-0.17	-0.058	-0.040	-8.4E-04	-0.0046	0	-0.0013	-0.28	0	-0.28
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
	Production of HOD bottle (Polycarb, 30 uses)	0.37	0.13	0.14	0.0043	0.024	0	0.0068	0.68	0	0.68
	Production of caps, closures	0.21	0.049	0.045	0.0019	0.010	0	0.0030	0.32	0.014	0.30
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (purified municipal)	0.094	0.011	0.33	0.11	0.016	0	0.030	0.60	0	0.60
	Filling (reusable drinking container filled once daily)	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi dist, 75 mi route)	0.067	1.41	0.031	0.011	0.0015	0	0.0028	1.52	0	1.52
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.56	0.029	0.85	0.29	0.040	0	0.077	1.85	0	1.85
	Industrial washing of HOD container	0.024	0.0033	0.075	0.023	0.0053	0	0.0066	0.14	0	0.14
	Wastewater treatment	0.0015	2.4E-04	0.0048	0.0015	2.1E-04	0	3.9E-04	0.0086	0	0.0086
	Chilling (HOD chiller unit)	0.31	0.037	1.11	0.38	0.053	0	0.10	2.00	0	2.00
	End of life management - HOD 100% recycling, container 0%	0.0031	0.0042	0.0077	-3.1E-05	0.0020	0	4.8E-04	0.018	0	0.018
	End of life management - caps & closures	-3.5E-04	0.0025	-0.0016	-5.5E-04	-7.6E-05	0	-1.5E-04	-2.7E-04	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**1.55**	**1.69**	**2.68**	**0.89**	**0.17**	**0**	**0.23**	**7.22**	**0.014**	**7.21**
	Percent by fuel	21%	23%	37%	12%	2%	0%	3%	100%		
HOD nat											
42	Credit for recycling (method 1)	-0.13	-0.044	-0.030	-6.3E-04	-0.0035	0	-9.9E-04	-0.21	0	-0.21
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
	Production of HOD bottle (Polycarb, 40 uses)	0.28	0.096	0.11	0.0033	0.018	0	0.0051	0.51	0	0.51
	Production of caps, closures	0.21	0.049	0.045	0.0019	0.010	0	0.0030	0.32	0.014	0.30
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (natural)	0.046	0.0054	0.16	0.056	0.0077	0	0.015	0.29	0	0.29
	Filling (reusable drinking container filled once daily)	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi dist, 75 mi route)	0.067	1.41	0.031	0.011	0.0015	0	0.0028	1.52	0	1.52
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.56	0.029	0.85	0.29	0.040	0	0.077	1.85	0	1.85
	Industrial washing of HOD container	0.024	0.0033	0.075	0.023	0.0053	0	0.0066	0.14	0	0.14
	Wastewater treatment	0.0012	1.8E-04	0.0037	0.0012	1.6E-04	0	3.1E-04	0.0067	0	0.0067
	Chilling (HOD chiller unit)	0.31	0.037	1.11	0.38	0.053	0	0.10	2.00	0	2.00
	End of life management - HOD 100% recycling, container 0%	0.0023	0.0035	0.0058	-2.1E-05	0.0015	0	3.6E-04	0.014	0	0.014
	End of life management - caps & closures	-3.5E-04	0.0025	-0.0016	-5.5E-04	-7.6E-05	0	-1.5E-04	-2.7E-04	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**1.45**	**1.67**	**2.48**	**0.83**	**0.16**	**0**	**0.22**	**6.81**	**0.014**	**6.80**
	Percent by fuel	21%	25%	36%	12%	2%	0%	3%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
HOD 200 mi distrib											
43	Credit for recycling (method 1)	-0.13	-0.044	-0.030	-6.3E-04	-0.0035	0	-9.9E-04	-0.21	0	-0.21
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
	Production of HOD bottle (Polycarb, 40 uses)	0.28	0.096	0.11	0.0033	0.018	0	0.0051	0.51	0	0.51
	Production of caps, closures	0.21	0.049	0.045	0.0019	0.010	0	0.0030	0.32	0.014	0.30
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (purified municipal)	0.094	0.011	0.33	0.11	0.016	0	0.030	0.60	0	0.60
	Filling (reusable drinking container filled once daily)	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (200 mi dist, 75 mi route)	0.11	2.41	0.053	0.018	0.0025	0	0.0048	2.61	0	2.61
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.56	0.029	0.85	0.29	0.040	0	0.077	1.85	0	1.85
	Industrial washing of HOD container	0.024	0.0033	0.075	0.023	0.0053	0	0.0066	0.14	0	0.14
	Wastewater treatment	0.0015	2.4E-04	0.0048	0.0015	2.1E-04	0	3.9E-04	0.0086	0	0.0086
	Chilling (HOD chiller unit)	0.31	0.037	1.11	0.38	0.053	0	0.10	2.00	0	2.00
	End of life management - HOD 100% recycling, container 0%	0.0023	0.0035	0.0058	-2.1E-05	0.0015	0	3.6E-04	0.014	0	0.014
	End of life management - caps & closures	-3.5E-04	0.0025	-0.0016	-5.5E-04	-7.6E-05	0	-1.5E-04	-2.7E-04	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**1.55**	**2.68**	**2.67**	**0.90**	**0.17**	**0**	**0.23**	**8.20**	**0.014**	**8.19**
	Percent by fuel	19%	33%	33%	11%	2%	0%	3%	100%		
HOD 50 mi route											
44	Credit for recycling (method 1)	-0.13	-0.044	-0.030	-6.3E-04	-0.0035	0	-9.9E-04	-0.21	0	-0.21
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
	Production of HOD bottle (Polycarb, 40 uses)	0.28	0.096	0.11	0.0033	0.018	0	0.0051	0.51	0	0.51
	Production of caps, closures	0.21	0.049	0.045	0.0019	0.010	0	0.0030	0.32	0.014	0.30
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (purified municipal)	0.094	0.011	0.33	0.11	0.016	0	0.030	0.60	0	0.60
	Filling (reusable drinking container filled once daily)	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi dist, 50 mi route)	0.050	1.05	0.023	0.0079	0.0011	0	0.0021	1.13	0	1.13
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.56	0.029	0.85	0.29	0.040	0	0.077	1.85	0	1.85
	Industrial washing of HOD container	0.024	0.0033	0.075	0.023	0.0053	0	0.0066	0.14	0	0.14
	Wastewater treatment	0.0015	2.4E-04	0.0048	0.0015	2.1E-04	0	3.9E-04	0.0086	0	0.0086
	Chilling (HOD chiller unit)	0.31	0.037	1.11	0.38	0.053	0	0.10	2.00	0	2.00
	End of life management - HOD 100% recycling, container 0%	0.0023	0.0035	0.0058	-2.1E-05	0.0015	0	3.6E-04	0.014	0	0.014
	End of life management - caps & closures	-3.5E-04	0.0025	-0.0016	-5.5E-04	-7.6E-05	0	-1.5E-04	-2.7E-04	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**1.48**	**1.32**	**2.64**	**0.89**	**0.17**	**0**	**0.23**	**6.73**	**0.014**	**6.72**
	Percent by fuel	22%	20%	39%	13%	2%	0%	3%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
HOD low chill											
45	Credit for recycling (method 1)	-0.13	-0.044	-0.030	-6.3E-04	-0.0035	0	-9.9E-04	-0.21	0	-0.21
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
	Production of HOD bottle (Polycarb, 40 uses)	0.28	0.096	0.11	0.0033	0.018	0	0.0051	0.51	0	0.51
	Production of caps, closures	0.21	0.049	0.045	0.0019	0.010	0	0.0030	0.32	0.014	0.30
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (purified municipal)	0.094	0.011	0.33	0.11	0.016	0	0.030	0.60	0	0.60
	Filling (reusable drinking container filled once daily)	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi dist, 75 mi route)	0.067	1.41	0.031	0.011	0.0015	0	0.0028	1.52	0	1.52
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.56	0.029	0.85	0.29	0.040	0	0.077	1.85	0	1.85
	Industrial washing of HOD container	0.024	0.0033	0.075	0.023	0.0053	0	0.0066	0.14	0	0.14
	Wastewater treatment	0.0015	2.4E-04	0.0048	0.0015	2.1E-04	0	3.9E-04	0.0086	0	0.0086
	Chilling (faster consumption = shorter chilling)	0.21	0.024	0.74	0.25	0.035	0	0.067	1.33	0	1.33
	End of life management - HOD 100% recycling, container 0%	0.0023	0.0035	0.0058	-2.1E-05	0.0015	0	3.6E-04	0.014	0	0.014
	End of life management - caps & closures	-3.5E-04	0.0025	-0.0016	-5.5E-04	-7.6E-05	0	-1.5E-04	-2.7E-04	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**1.39**	**1.66**	**2.28**	**0.76**	**0.15**	**0**	**0.20**	**6.45**	**0.014**	**6.44**
	Percent by fuel	22%	26%	35%	12%	2%	0%	3%	100%		
HOD high chill											
46	Credit for recycling (method 1)	-0.13	-0.044	-0.030	-6.3E-04	-0.0035	0	-9.9E-04	-0.21	0	-0.21
	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.070	0.080	0.10	0.060	0.024	0	0.0055	0.34	0	0.34
	Production of HOD bottle (Polycarb, 40 uses)	0.28	0.096	0.11	0.0033	0.018	0	0.0051	0.51	0	0.51
	Production of caps, closures	0.21	0.049	0.045	0.0019	0.010	0	0.0030	0.32	0.014	0.30
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (purified municipal)	0.094	0.011	0.33	0.11	0.016	0	0.030	0.60	0	0.60
	Filling (reusable drinking container filled once daily)	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi dist, 75 mi route)	0.067	1.41	0.031	0.011	0.0015	0	0.0028	1.52	0	1.52
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0.56	0.029	0.85	0.29	0.040	0	0.077	1.85	0	1.85
	Industrial washing of HOD container	0.024	0.0033	0.075	0.023	0.0053	0	0.0066	0.14	0	0.14
	Wastewater treatment	0.0015	2.4E-04	0.0048	0.0015	2.1E-04	0	3.9E-04	0.0086	0	0.0086
	Chilling (higher energy use)	0.37	0.044	1.34	0.46	0.063	0	0.12	2.40	0	2.40
	End of life management - HOD 100% recycling, container 0%	0.0023	0.0035	0.0058	-2.1E-05	0.0015	0	3.6E-04	0.014	0	0.014
	End of life management - caps & closures	-3.5E-04	0.0025	-0.0016	-5.5E-04	-7.6E-05	0	-1.5E-04	-2.7E-04	0	-2.7E-04
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**1.56**	**1.68**	**2.88**	**0.97**	**0.18**	**0**	**0.25**	**7.52**	**0.014**	**7.50**
	Percent by fuel	21%	22%	38%	13%	2%	0%	3%	100%		

Table 2-11. Energy Profile for Example Drinking Water Systems
(million Btu per 1,000 gallons)

		Nat. Gas	Petroleum	Coal	Hydro-power	Nuclear	Wood	Other	TOTAL	Energy Export Credit	NET
HOD best											
47	Credit for recycling (method 3)	-0.26	-0.088	-0.060	-0.0013	-0.0069	0	-0.0020	-0.42	0	-0.42
	Production of reusable drinking container (32 oz PET, used 5 yrs)	0.0038	0.0039	0.0019	7.6E-05	4.2E-04	0	1.2E-04	0.010	1.2E-04	0.010
	Production of HOD bottle (Polycarb, 40 uses)	0.28	0.096	0.11	0.0033	0.018	0	0.0051	0.51	0	0.51
	Production of caps, closures	0.20	0.045	0.042	0.0018	0.0097	0	0.0028	0.30	0.012	0.29
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (natural)	2.9E-04	3.0E-05	8.3E-04	2.8E-04	4.2E-05	0	7.5E-05	0.0015	0	0.0015
	Filling (reusable drinking container filled twice daily)	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (50 mi dist, 50 mi route)	0.050	1.05	0.023	0.0079	0.0011	0	0.0021	1.13	0	1.13
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (once/wk, low water use)	0.011	7.8E-04	0.023	0.0080	0.0011	0	0.0021	0.046	0	0.046
	Industrial washing of HOD container	0.024	0.0033	0.075	0.023	0.0053	0	0.0066	0.14	0	0.14
	Wastewater treatment	1.0E-04	1.6E-05	3.3E-04	1.0E-04	1.4E-05	0	2.7E-05	5.8E-04	0	5.8E-04
	Chilling (faster consumption = shorter chilling)	0.21	0.024	0.74	0.25	0.035	0	0.067	1.33	0	1.33
	End of life management - HOD 100% recycling, container 100%	0.0049	0.0015	0.013	5.6E-04	0.0031	0	8.9E-04	0.024	0	0.024
	End of life management - caps & closures	-3.2E-04	0.0023	-0.0015	-5.2E-04	-7.1E-05	0	-1.4E-04	-2.5E-04	0	-2.5E-04
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**0.52**	**1.14**	**0.98**	**0.30**	**0.068**	**0**	**0.086**	**3.10**	**0.013**	**3.09**
	Percent by fuel	17%	37%	32%	10%	2%	0%	3%	100%		
HOD worst											
48	Credit for recycling (method 1)	-0.081	-0.086	-0.018	-6.5E-04	-0.0036	0	-0.0010	-0.19	-0.0028	-0.19
	Production of reusable drinking container (16 oz drinking glass)	0.033	0.0090	0.0083	2.7E-04	0.0015	0	4.3E-04	0.052	0	0.052
	Production of HOD bottle (PET 10% heavier, 30 uses)	0.18	0.19	0.091	0.0037	0.020	0	0.0057	0.49	0.0056	0.49
	Production of caps, closures	0.20	0.044	0.041	0.0018	0.0097	0	0.0027	0.30	0.012	0.28
	Production of secondary packaging	0	0	0	0	0	0	0	0	0	0
	Water processing (purified municipal)	0.098	0.011	0.34	0.12	0.016	0	0.031	0.62	0	0.62
	Filling (reusable drinking container filled once daily)	0.0035	4.1E-04	0.013	0.0043	5.9E-04	0	0.0011	0.022	0	0.022
	Distribution of filled containers (200 mi dist, 100 mi route)	0.13	2.78	0.061	0.021	0.0029	0	0.0056	3.00	0	3.00
	Consumer transport	0	0	0	0	0	0	0	0	0	0
	Home washing of reusable drinking container (high water use, half full load)	1.41	0.073	2.13	0.73	0.10	0	0.19	4.64	0	4.64
	Industrial washing of HOD container	0.024	0.0033	0.075	0.023	0.0053	0	0.0066	0.14	0	0.14
	Wastewater treatment	0.0031	4.9E-04	0.010	0.0031	4.3E-04	0	8.2E-04	0.018	0	0.018
	Chilling (higher energy use)	0.37	0.044	1.34	0.46	0.063	0	0.12	2.40	0	2.40
	End of life management - HOD 100% recycling, container 0%	0.0035	0.0044	0.0090	1.4E-04	0.0023	0	5.8E-04	0.020	0	0.020
	End of life management - caps & closures	-3.2E-04	0.0023	-0.0015	-5.1E-04	-7.1E-05	0	-1.4E-04	-2.5E-04	0	-2.5E-04
	End of life management - secondary packaging	0	0	0	0	0	0	0	0	0	0
	TOTAL	**2.38**	**3.08**	**4.10**	**1.36**	**0.22**	**0**	**0.37**	**11.5**	**0.015**	**11.5**
	Percent by fuel	21%	27%	36%	12%	2%	0%	3%	100%		

Figure 2-1. Energy Results for Bottled Water Subscenarios (million Btu per 1,000 gallons)

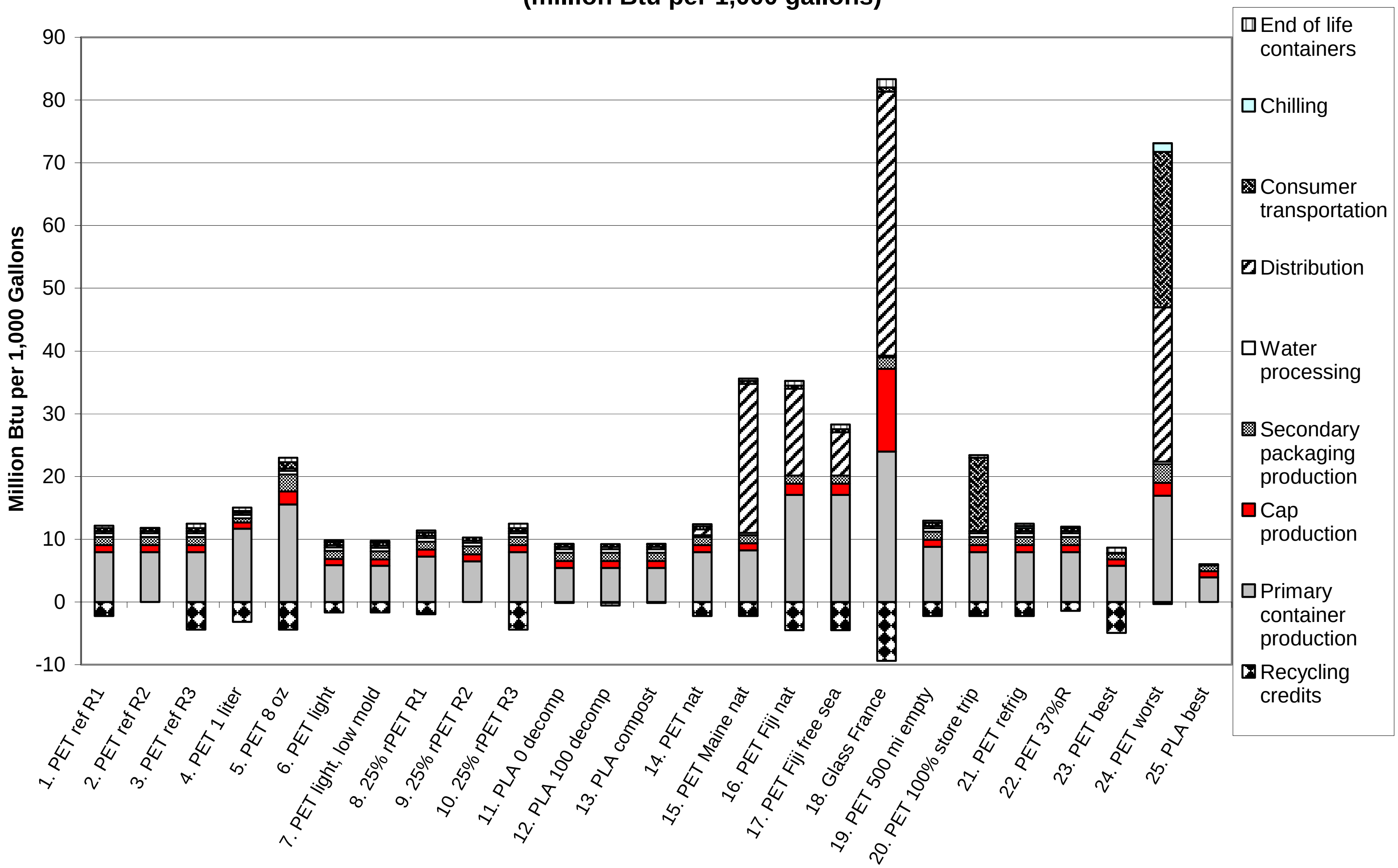


Figure 2-2. Energy Results for Bottled Water Subscenarios excluding long-distance transport scenarios (million Btu per 1,000 gallons)

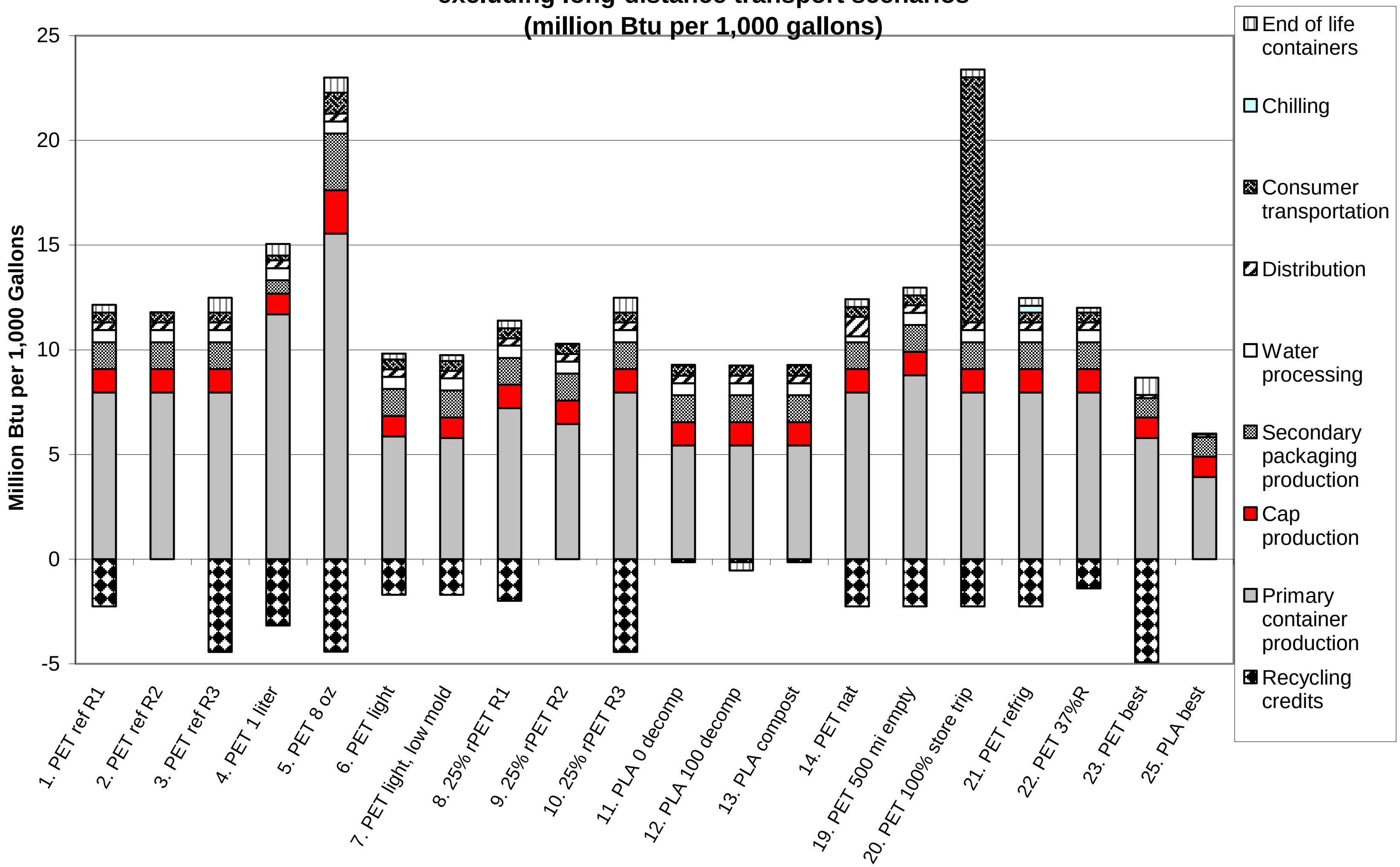


Figure 2-3. Energy Results for Tap and HOD Water Subscenarios (million Btu per 1,000 gallons)

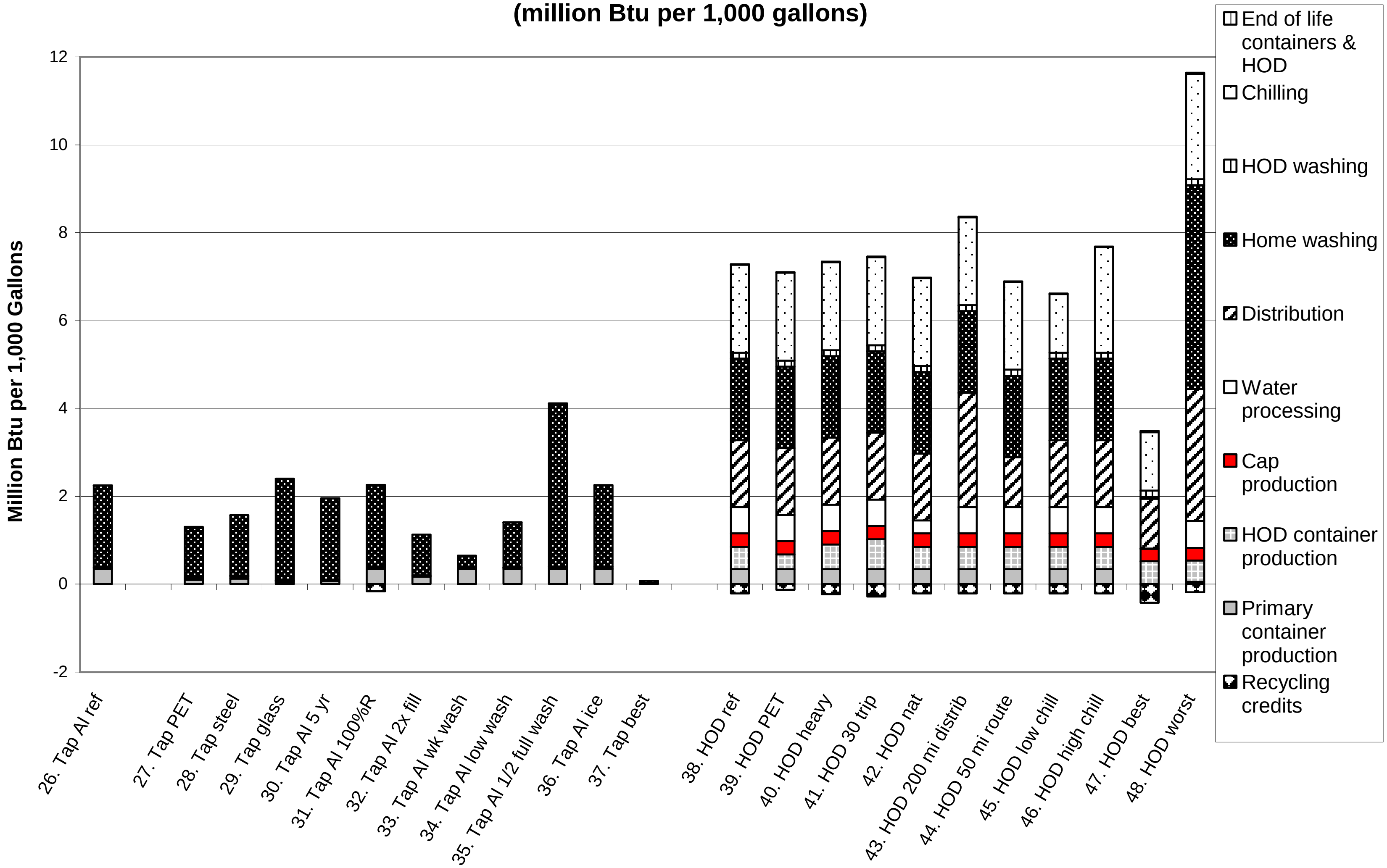


Figure 2-4. Net Energy Results for Bottled Water Subscenarios (million Btu per 1,000 gallons)

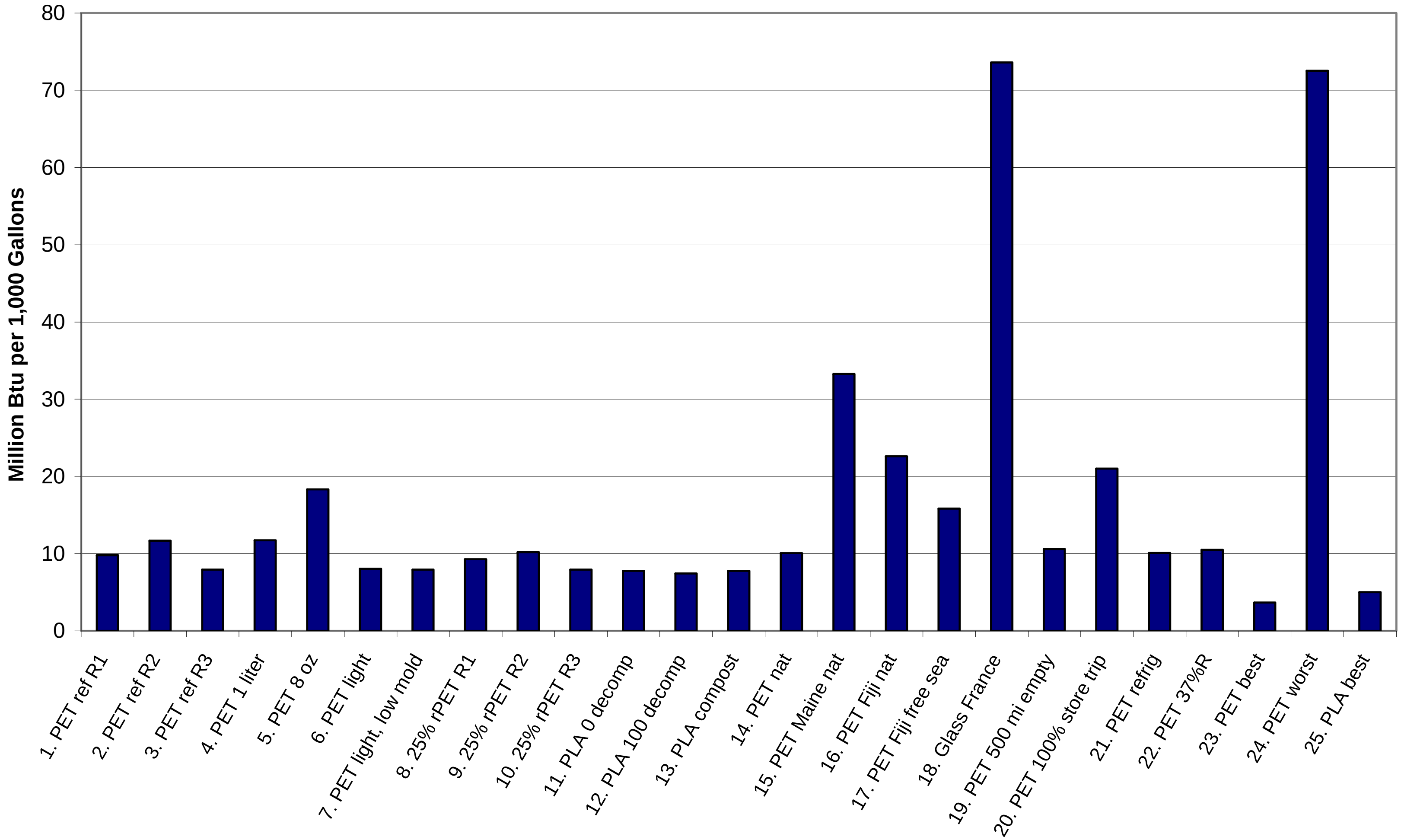
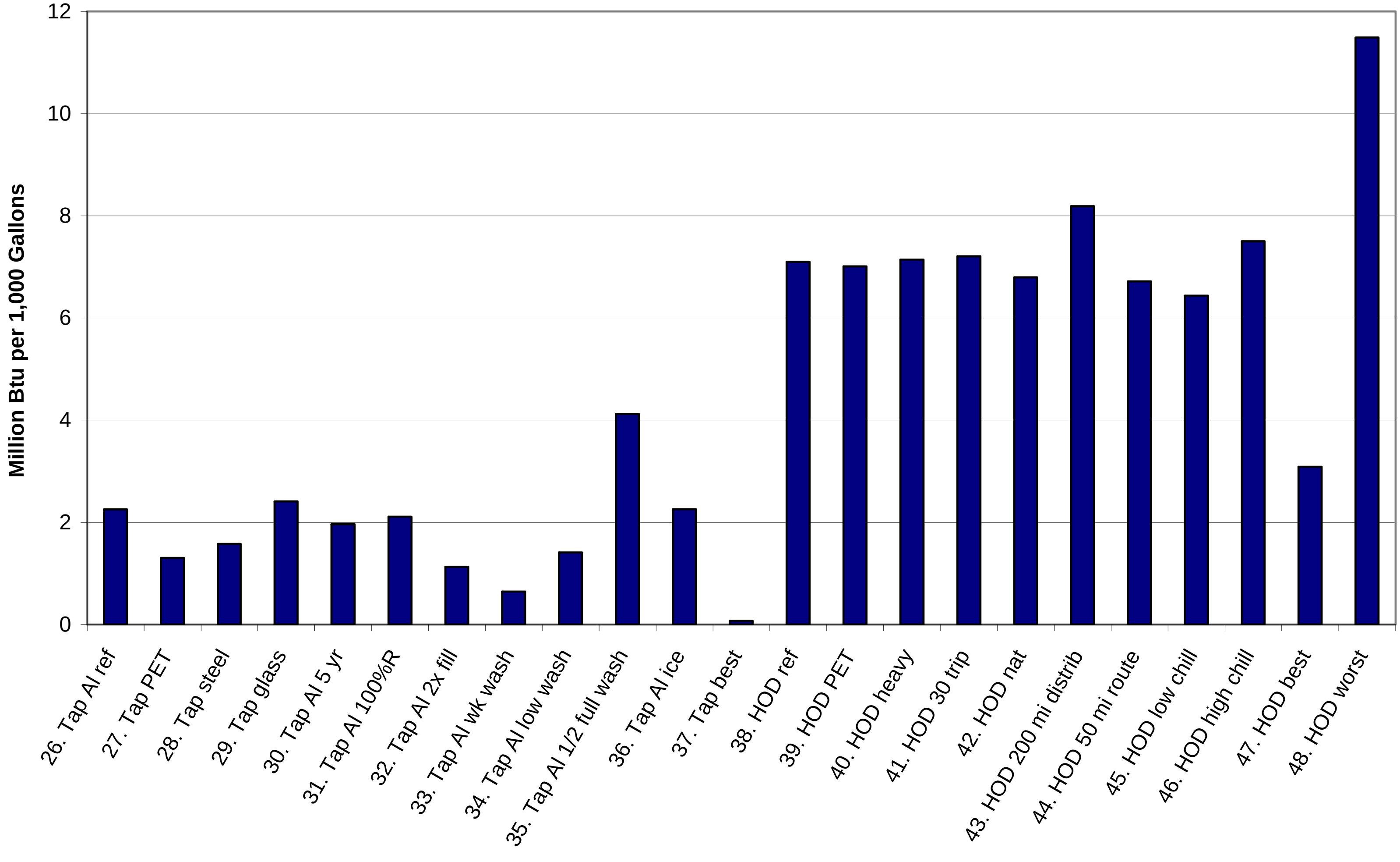


Figure 2-5. Net Energy Results for Tap and HOD Water Subscenarios
(million Btu per 1,000 gallons)



Solid Waste Results

Solid waste results by life cycle stage and by solid waste category for all 48 drinking water subscenarios are presented in Table 2-12 for solid waste by weight and in Table 2-13 for solid waste by volume. Solid waste weight results by life cycle stage are presented graphically for all bottled water systems in Figure 2-6 and with long-distance transport scenarios excluded in Figure 2-7. Figure 2-8 shows results by life cycle stage for tap water and HOD subscenarios. For solid waste by volume, results by life cycle stage are shown in Figures 2-9 and 2-10 for bottled water and in Figure 2-11 for tap and HOD water subscenarios. Additional modeling details for each subscenario shown in the figures can be viewed in Table 2-9.

Bottled Water Solid Waste. Solid waste for the PET bottle system is dominated by disposal of postconsumer containers, lids, and packaging. On average, 75 percent of the total solid waste for each system is postconsumer, with the containers accounting for nearly half of total solid waste. The lowest postconsumer solid waste is for scenario 13, the PLA scenario with 100% composting, which diverts all the bottle material from landfill disposal. The highest postconsumer solid wastes are for the glass bottle system. The next highest solid wastes are for the 8 ounce PET bottle, which has the highest packaging to water weight ratio, and the imported Fiji bottle, which is heavier than other 16.9 ounce bottle samples.

The weight of secondary packaging is based on the average weights of corrugated and film used in three types of case packaging systems: corrugated tray with film wrap, corrugated pad with film wrap, and all-film package. Because of the high postconsumer recycling rate for corrugated (76.3 percent in Oregon in 2005), the majority of the postconsumer secondary packaging waste disposed is film.

Scenarios 1 through 3 show the same virgin bottled water scenario evaluated for each of the three recycling methodologies. Table 2-12 shows that the weight of postconsumer waste allocated to the bottle system is lowest for methodologies 2 and 3, because this method transfers all the disposal burdens for recovered bottle material to the user of the recycled resin. Methodology 1, the open-loop methodology, divides the material disposal burdens for recycled bottles between the two systems using the material, the bottle system and the subsequent user system.

Tap Water Solid Waste. The tap water system is the least material-intensive system, and thus the solid waste results are dominated by the fuel-related wastes for container washing. Among the four types of reusable drinking containers evaluated, the weight of container production wastes is greatest for the virgin aluminum container, mainly from the ore processing wastes from aluminum production and the fuel-related wastes from the high energy requirements for processing ore into aluminum. The weight of postconsumer drinking containers is highest for the drinking glass, which is the smallest but heaviest of the containers.

HOD Water Solid Waste. The HOD system results are also dominated by fuel-related wastes, largely those associated with energy use for container washing and water chilling. On average across all HOD subscenarios, the weight of postconsumer containers and lids accounts for approximately 18 percent of the total weight of solid waste.

Solid Waste by Volume. Solid weight waste results shown in Table 2-12 are converted to the volume basis shown in Table 2-13 using landfill densities that take into account not only the density of the material as put into the landfill but also the degree to which the material compacts in the landfill. Because the volume of postconsumer combustion ash is so low, it is included in the total volume of postconsumer weight in Table 2-13 rather than shown separately. Because the fabricated containers and lids compact less densely in the landfill compared to industrial solid wastes (process and fuel-related wastes), postconsumer waste accounts for a higher percentage of the total volume of solid waste compared to its percentage of total weight of solid waste for each system.

Atmospheric and Waterborne Emissions

Process- and fuel-related emissions tables are not included in the report due to their length and the number of subscenarios considered, but the tables will be made available electronically. The emissions inventories for the drinking water systems are not discussed in this chapter but are used to calculate the impacts in Chapter 3.

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios
(pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
PET ref R1						
1	Production of PET bottle	7.92	41.7	0	0	49.6
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.23	6.07	0	0	7.30
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	6.88	3.45	142	0	153
	End of life management - caps & closures	0	-0.19	24.8	0	24.7
	End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
	Credit for recycling (method 1)	-0.98	-11.8	0	0	-12.7
	TOTAL	**18.4**	**59.2**	**208**	**0.073**	**286**
	Percent by category	6.4%	20.7%	72.9%	0.0%	100.0%
PET ref R2						
2	Production of PET bottle	7.92	41.7	0	0	49.6
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.23	6.07	0	0	7.30
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0	-0.32	78.4	0	78.1
	End of life management - caps & closures	0	-0.19	24.8	0	24.7
	End of life management - secondary packaging	0	-0.31	29.3	0.028	29.0
	Credit for recycling (method 2)	0	0	0	0	0
	TOTAL	**12.5**	**67.3**	**133**	**0.028**	**212**
	Percent by category	5.9%	31.7%	62.4%	0.0%	100.0%
PET ref R3						
3	Production of PET bottle	7.92	41.7	0	0	49.6
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.23	6.07	0	0	7.30
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	13.8	7.74	78.4	0	99.9
	End of life management - caps & closures	0	-0.19	24.8	0	24.7
	End of life management - secondary packaging	0	-0.28	29.3	0.028	29.0
	Credit for recycling (method 3)	-1.97	-23.2	0	0	-25.2
	TOTAL	**24.3**	**52.2**	**133**	**0.028**	**209**
	Percent by category	11.6%	25.0%	63.4%	0.0%	100.0%

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios
(pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
PET 1 liter						
4	Production of PET bottle (1 liter)	11.6	61.3	0	0	72.9
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.08	5.31	0	0	6.39
	Production of secondary packaging	1.66	3.78	0	0	5.44
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.88	0	0	0.88
	Consumer transport (4% allocated to water)	0	0.55	0	0	0.55
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	10.1	5.07	209	0	224
	End of life management - caps & closures	0	-0.16	21.7	0	21.6
	End of life management - secondary packaging	0	-0.23	20.6	0.037	20.4
	Credit for recycling (method 1)	-0.49	-15.2	0	0	-15.7
	TOTAL	**24.0**	**72.1**	**252**	**0.037**	**348**
	Percent by category	6.9%	20.7%	72.4%	0.0%	100.0%
PET 8 oz						
5	Production of PET bottle (8 oz)	15.5	81.4	0	0	96.9
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	2.28	11.2	0	0	13.5
	Production of secondary packaging	7.01	16.0	0	0	23.0
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.90	0	0	0.90
	Consumer transport (4% allocated to water)	0	2.29	0	0	2.29
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	13.4	6.74	278	0	298
	End of life management - caps & closures	0	-0.35	45.9	0	45.6
	End of life management - secondary packaging	0	-0.97	87.0	0.16	86.1
	Credit for recycling (method 1)	-2.08	-23.3	0	0	-25.4
	TOTAL	**36.1**	**105**	**411**	**0.16**	**552**
	Percent by category	6.5%	19.0%	74.4%	0.0%	100.0%
PET light						
6	Production of PET bottle (lightweighted)	5.84	30.7	0	0	36.6
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.08	5.31	0	0	6.39
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	5.07	2.54	105	0	113
	End of life management - caps & closures	0	-0.16	21.7	0	21.6
	End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
	Credit for recycling (method 1)	-0.98	-9.22	0	0	-10.2
	TOTAL	**14.3**	**49.1**	**168**	**0.073**	**231**
	Percent by category	6.2%	21.2%	72.6%	0.0%	100.0%

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios
(pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
PET light, low mold						
7	Production of PET bottle (lightweight, lower molding energy)	5.84	29.4	0	0	35.2
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.08	5.31	0	0	6.39
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	5.07	2.54	105	0	113
	End of life management - caps & closures	0	-0.16	21.7	0	21.6
	End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
	Credit for recycling (method 1)	-0.98	-9.22	0	0	-10.2
	TOTAL	**14.3**	**47.8**	**168**	**0.073**	**230**
	Percent by category	6.2%	20.8%	73.0%	0.0%	100.0%
25% rPET R1						
8	Production of PET bottle (25% recycled content)	9.74	40.3	0	0	50.0
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.23	6.07	0	0	7.30
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	6.88	3.52	125	0	135
	End of life management - caps & closures	0	-0.19	24.8	0	24.7
	End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
	Credit for recycling (method 1)	-0.98	-10.6	0	0	-11.5
	TOTAL	**20.2**	**59.1**	**191**	**0.073**	**270**
	Percent by category	7.5%	21.9%	70.6%	0.0%	100.0%
25% rPET R2						
9	Production of PET bottle (25% recycled content)	11.6	38.9	0	0	50.5
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.23	6.07	0	0	7.30
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	0	-0.32	78.4	0	78.1
	End of life management - caps & closures	0	-0.19	24.8	0	24.7
	End of life management - secondary packaging	0	-0.31	29.3	0.028	29.0
	Credit for recycling (method 2)	0	0	0	0	0
	TOTAL	**16.1**	**64.5**	**133**	**0.028**	**213**
	Percent by category	7.6%	30.3%	62.2%	0.0%	100.0%

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios (pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
25% rPET R3						
10	Production of PET bottle (25% recycled content)	7.92	41.7	0	0	49.6
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.23	6.07	0	0	7.30
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	13.8	7.74	78.4	0	99.9
	End of life management - caps & closures	0	-0.19	24.8	0	24.7
	End of life management - secondary packaging	0	-0.28	29.3	0.028	29.0
	Credit for recycling (method 3)	-1.97	-23.2	0	0	-25.2
	TOTAL	**24.3**	**52.2**	**133**	**0.028**	**209**
	Percent by category	11.6%	25.0%	63.4%	0.0%	100.0%
PLA 0 decomp						
11	Production of PLA bottle	2.38	58.7	0	0	61.0
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.23	6.07	0	0	7.30
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 0% decomposition	0	-0.65	213	0	213
	End of life management - caps & closures	0	-0.19	24.8	0	24.7
	End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
	Credit for recycling (method 1)	-0.98	-2.13	0	0	-3.11
	TOTAL	**5.94**	**45.1**	**279**	**0.073**	**330**
	Percent by category	1.8%	13.7%	84.5%	0.0%	100.0%
PLA 100 decomp						
12	Production of PLA bottle	2.38	58.7	0	0	61.0
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.23	6.07	0	0	7.30
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 100% decomposition	0	-8.65	213	0	205
	End of life management - caps & closures	0	-0.19	24.8	0	24.7
	End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
	Credit for recycling (method 1)	-0.98	-2.13	0	0	-3.11
	TOTAL	**5.94**	**37.1**	**279**	**0.073**	**322**
	Percent by category	1.8%	11.5%	86.6%	0.0%	100.0%

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios
(pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
PLA compost						
13	Production of PLA bottle	2.38	58.7	0	0	61.0
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.23	6.07	0	0	7.30
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 100% composting	11.5	-0.69	0	0	10.8
	End of life management - caps & closures	0	-0.19	24.8	0	24.7
	End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
	Credit for recycling (method 1)	-0.98	-2.13	0	0	-3.11
	TOTAL	**17.4**	**45.1**	**66.0**	**0.073**	**129**
	Percent by category	13.5%	35.1%	51.3%	0.1%	100.0%
PET nat						
14	Production of PET bottle	7.92	41.7	0	0	49.6
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.23	6.07	0	0	7.30
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (natural)	0	4.98	0	0	4.98
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (130 mi)	0	2.27	0	0	2.27
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0	0	0	0
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	6.88	3.45	142	0	153
	End of life management - caps & closures	0	-0.19	24.8	0	24.7
	End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
	Credit for recycling (method 1)	-0.98	-11.8	0	0	-12.7
	TOTAL	**18.4**	**55.1**	**208**	**0.073**	**282**
	Percent by category	6.5%	19.5%	73.9%	0.0%	100.0%
PET Maine nat						
15	Production of PET bottle	7.92	47.1	0	0	55.0
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.23	6.07	0	0	7.30
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (natural)	0	6.47	0	0	6.47
	Filling	0	0.52	0	0	0.52
	Distribution of filled containers from Maine	0	57.1	0	0	57.1
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0	0	0	0
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	6.88	3.45	142	0	153
	End of life management - caps & closures	0	-0.19	24.8	0	24.7
	End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
	Credit for recycling (method 1)	-0.98	-11.8	0	0	-12.7
	TOTAL	**18.4**	**117**	**208**	**0.073**	**344**
	Percent by category	5.3%	34.0%	60.6%	0.0%	100.0%

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios
(pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
PET Fiji nat						
16	Production of PET bottle	16.4	97.3	0	0	114
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	2.00	9.87	0	0	11.9
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (natural)	0	0.0097	0	0	0.0097
	Filling	0	0.52	0	0	0.52
	Distribution of filled containers from Fiji	0	33.3	0	0	33.3
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0	0	0	0
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	14.2	7.14	294	0	316
	End of life management - caps & closures	0	-0.31	40.4	0	40.1
	End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
	Credit for recycling (method 1)	-0.98	-22.0	0	0	-23.0
	TOTAL	**34.9**	**134**	**376**	**0.073**	**545**
	Percent by category	6.4%	24.6%	69.0%	0.0%	100.0%
PET Fiji free sea						
17	Production of PET bottle	16.4	97.3	0	0	114
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	2.00	9.87	0	0	11.9
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (natural)	0	0.0097	0	0	0.0097
	Filling	0	0.52	0	0	0.52
	Distribution of filled containers from Fiji (discounted ocean)	0	16.6	0	0	16.6
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0	0	0	0
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	14.2	7.14	294	0	316
	End of life management - caps & closures	0	-0.31	40.4	0	40.1
	End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
	Credit for recycling (method 1)	-0.98	-22.0	0	0	-23.0
	TOTAL	**34.9**	**117**	**376**	**0.073**	**528**
	Percent by category	6.6%	22.2%	71.2%	0.0%	100.0%
Glass France						
18	Production of glass bottle	256	101	0	0	357
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	14.5	71.5	0	0	86.1
	Production of secondary packaging	4.63	10.6	0	0	15.2
	Water processing (natural)	0	3.44	0	0	3.44
	Filling	0	0.28	0	0	0.28
	Distribution of filled containers from France	0	86.6	0	0	86.6
	Consumer transport (4% allocated to water)	0	1.52	0	0	1.52
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0	0	0	0
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 74% recycling	0	14.6	3,304	249	3,567
	End of life management - caps & closures	0	-2.22	293	0	291
	End of life management - secondary packaging	0	-0.64	57.5	0.10	57.0
	Credit for recycling (method 1)	-96.0	-57.9	0	0	-154
	TOTAL	**179**	**229**	**3,654**	**249**	**4,311**
	Percent by category	4.1%	5.3%	84.8%	5.8%	100.0%

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios
(pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
PET 500 mi empty						
19	Production of PET bottle (molded offsite)	7.92	43.7	0	0	51.6
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.23	6.07	0	0	7.30
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
	Consumer transport (4% allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	6.88	3.45	142	0	153
	End of life management - caps & closures	0	-0.19	24.8	0	24.7
	End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
	Credit for recycling (method 1)	-0.98	-11.8	0	0	-12.7
	TOTAL	**18.4**	**61.2**	**208**	**0.073**	**288**
	Percent by category	6.4%	21.2%	72.4%	0.0%	100.0%
PET 100% store trip						
20	Production of PET bottle	7.92	41.7	0	0	49.6
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.23	6.07	0	0	7.30
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
	Consumer transport (100% of trip allocated to water)	0	27.1	0	0	27.1
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 62% recycling	6.88	3.45	142	0	153
	End of life management - caps & closures	0	-0.19	24.8	0	24.7
	End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
	Credit for recycling (method 1)	-0.98	-11.8	0	0	-12.7
	TOTAL	**18.4**	**85.1**	**208**	**0.073**	**312**
	Percent by category	5.9%	27.3%	66.8%	0.0%	100.0%
PET refrig						
21	Production of PET bottle	7.92	41.7	0	0	49.6
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.23	6.07	0	0	7.30
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
	Consumer transport (4% of trip allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (3.5 days home refrig)	0	5.82	0	0	5.82
	End of life management - bottles @ 62% recycling	6.88	3.45	142	0	153
	End of life management - caps & closures	0	-0.19	24.8	0	24.7
	End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
	Credit for recycling (method 1)	-0.98	-11.8	0	0	-12.7
	TOTAL	**18.4**	**65.0**	**208**	**0.073**	**292**
	Percent by category	6.3%	22.3%	71.4%	0.0%	100.0%

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios
(pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
PET 37%R						
22	Production of PET bottle	7.92	41.7	0	0	49.6
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.23	6.07	0	0	7.30
	Production of secondary packaging	3.32	7.56	0	0	10.9
	Water processing (purified municipal)	2.4E-04	10.4	0	0	10.4
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi)	0	0.87	0	0	0.87
	Consumer transport (4% of trip allocated to water)	0	1.09	0	0	1.09
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.034	0	0	0.034
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 37% recycling	4.10	1.72	168	0	174
	End of life management - caps & closures	0	-0.19	24.8	0	24.7
	End of life management - secondary packaging	0	-0.46	41.2	0.073	40.8
	Credit for recycling (method 1)	-0.98	-7.87	0	0	-8.86
	TOTAL	**15.6**	**61.3**	**234**	**0.073**	**311**
	Percent by category	5.0%	19.7%	75.3%	0.0%	100.0%
PET best						
23	Production of PET bottle (lightweight, 25% recycl cont)	5.84	29.4	0	0	35.2
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.08	5.31	0	0	6.39
	Production of secondary packaging (film only)	0.76	2.04	0	0	2.80
	Water processing (natural)	0	0.0074	0	0	0.0074
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (20 mi)	0	0.35	0	0	0.35
	Consumer transport (0% of trip allocated to water)	0	0.0073	0	0	0.0073
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0	0	0	0
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 100% recycling	16.3	9.57	0	0	25.9
	End of life management - caps & closures	0	-0.16	21.7	0	21.6
	End of life management - secondary packaging	0	-0.21	22.5	0	22.3
	Credit for recycling (method 3)	0	-22.5	0	0	-22.5
	TOTAL	**24.0**	**24.2**	**44.2**	**0**	**92.4**
	Percent by category	26.0%	26.2%	47.9%	0.0%	100.0%
PET worst						
24	Production of PET bottle (8 oz, molded off-site)	15.5	93.9	0	0	109
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	2.28	11.2	0	0	13.5
	Production of secondary packaging	7.67	17.5	0	0	25.1
	Water processing (natural)	0	7.19	0	0	7.19
	Filling	0	0.52	0	0	0.52
	Distribution of filled containers from Maine	0	59.1	0	0	59.1
	Consumer transport (100% of trip allocated to water)	0	57.2	0	0	57.2
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.0014	0	0	0.0014
	Chilling (1 wk home refrig)	0	24.6	0	0	24.6
	End of life management - bottles @ 0% recycling	0	-1.63	403	0	402
	End of life management - caps & closures	0	-0.35	45.9	0	45.6
	End of life management - secondary packaging	0	-1.06	95.1	0.17	94.2
	Credit for recycling (method 1)	-2.27	-4.92	0	0	-7.19
	TOTAL	**23.2**	**263**	**544**	**0.17**	**831**
	Percent by category	2.8%	31.7%	65.5%	0.0%	100.0%

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios
(pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
PLA best						
25	Production of PLA bottle	1.75	41.9	0	0	43.6
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	1.08	5.31	0	0	6.39
	Production of secondary packaging (film only)	0.76	2.04	0	0	2.80
	Water processing (natural)	0	0.0074	0	0	0.0074
	Filling	0	0.40	0	0	0.40
	Distribution of filled containers (20 mi)	0	0.35	0	0	0.35
	Consumer transport (0% of trip allocated to water)	0	0.0073	0	0	0.0073
	Home washing of reusable drinking container	0	0	0	0	0
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0	0	0	0
	Chilling (none)	0	0	0	0	0
	End of life management - bottles @ 0% decomposition	0	-0.48	157	0	156
	End of life management - caps & closures	0	-0.16	21.7	0	21.6
	End of life management - secondary packaging	0	-0.21	22.5	0	22.3
	Credit for recycling (method 3)	0	0	0	0	0
	TOTAL	**3.59**	**22.3**	**201**	**0**	**227**
	Percent by category	1.6%	9.8%	88.6%	0.0%	100.0%
Tap Al ref						
26	Production of reusable drinking container (20 oz aluminum, 1 yr use)	11.6	3.43	0	0	15.0
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	0.022	0.11	0	0	0.13
	Production of secondary packaging	0	0	0	0	0
	Water processing (tap)	2.6E-04	0.48	0	0	0.48
	Filling (reusable drinking container filled once daily)	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	27.7	0	0	27.7
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.11	0	0	0.11
	Chilling (none)	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	0.0032	3.59	0.27	3.87
	End of life management - caps & closures	0	-0.0034	0.45	0	0.45
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0	0
	TOTAL	**11.6**	**31.9**	**4.04**	**0.27**	**47.8**
	Percent by category	24.3%	66.6%	8.5%	0.6%	100.0%
Tap PET						
27	Production of reusable drinking container (32 oz PET, 1 yr use)	0.11	0.65	0	0	0.75
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	0.020	0.099	0	0	0.12
	Production of secondary packaging	0	0	0	0	0
	Water processing (tap)	2.2E-04	0.40	0	0	0.40
	Filling (reusable drinking container filled once daily)	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	17.3	0	0	17.3
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.069	0	0	0.069
	Chilling (none)	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	-0.0094	2.33	0	2.33
	End of life management - caps & closures	0	-0.0031	0.40	0	0.40
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0	0
	TOTAL	**0.13**	**18.5**	**2.74**	**0**	**21.4**
	Percent by category	0.6%	86.6%	12.8%	0.0%	100.0%

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios (pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
Tap steel						
28	Production of reusable drinking container (27 oz steel, 1 yr use)	1.90	1.61	0	0	3.51
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	0.049	0.24	0	0	0.29
	Production of secondary packaging	0	0	0	0	0
	Water processing (tap)	2.3E-04	0.42	0	0	0.42
	Filling (reusable drinking container filled once daily)	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	20.5	0	0	20.5
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.081	0	0	0.081
	Chilling (none)	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	0.0042	6.04	0.45	6.50
	End of life management - caps & closures	0	-0.0074	0.98	0	0.97
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0	0
	TOTAL	**1.95**	**22.9**	**7.02**	**0.45**	**32.3**
	Percent by category	6.0%	70.8%	21.7%	1.4%	100.0%
Tap glass						
29	Production of reusable drinking container (16 oz drinking glass, 1 yr use)	0.54	0.31	0	0	0.85
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	0	0	0	0	0
	Production of secondary packaging	0	0	0	0	0
	Water processing (tap)	2.9E-04	0.53	0	0	0.53
	Filling (reusable drinking container filled once daily)	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	34.7	0	0	34.7
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.14	0	0	0.14
	Chilling (none)	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	0.0028	11.0	0.83	11.8
	End of life management - caps & closures	0	0	0	0	0
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0	0
	TOTAL	**0.54**	**35.7**	**11.0**	**0.83**	**48.0**
	Percent by category	1.1%	74.2%	22.9%	1.7%	100.0%
Tap Al 5 yr						
30	Production of reusable drinking container (20 oz aluminum, 5 yrs use)	2.32	0.69	0	0	3.01
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	0.0045	0.022	0	0	0.026
	Production of secondary packaging	0	0	0	0	0
	Water processing (tap)	2.6E-04	0.48	0	0	0.48
	Filling (reusable drinking container filled once daily)	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	27.7	0	0	27.7
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.11	0	0	0.11
	Chilling (none)	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	6.5E-04	0.72	0.054	0.77
	End of life management - caps & closures	0	-6.8E-04	0.090	0	0.089
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0	0
	TOTAL	**2.33**	**29.0**	**0.81**	**0.054**	**32.2**
	Percent by category	7.2%	90.1%	2.5%	0.2%	100.0%

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios
(pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
Tap Al 100%R						
31	Production of reusable drinking container (20 oz aluminum, 1 yr use)	11.6	3.43	0	0	15.0
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	0.022	0.11	0	0	0.13
	Production of secondary packaging	0	0	0	0	0
	Water processing (tap)	2.6E-04	0.48	0	0	0.48
	Filling (reusable drinking container filled once daily)	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	27.7	0	0	27.7
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.11	0	0	0.11
	Chilling (none)	0	0	0	0	0
	End of life management - drinking containers @ 100% recycling	0.16	0.13	1.80	0.14	2.22
	End of life management - caps & closures	0	-0.0034	0.45	0	0.45
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	-5.81	-1.63	0	0	-7.43
	TOTAL	**5.99**	**30.4**	**2.24**	**0.14**	**38.7**
	Percent by category	15.5%	78.4%	5.8%	0.3%	100.0%
Tap Al 2x fill						
32	Production of reusable drinking container (20 oz aluminum, 1 yr use)	5.81	1.72	0	0	7.52
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	0.011	0.055	0	0	0.066
	Production of secondary packaging	0	0	0	0	0
	Water processing (tap)	2.0E-04	0.37	0	0	0.37
	Filling (reusable drinking container filled twice daily)	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	13.9	0	0	13.9
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.055	0	0	0.055
	Chilling (none)	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	0.0016	1.80	0.14	1.93
	End of life management - caps & closures	0	-0.0017	0.22	0	0.22
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0	0
	TOTAL	**5.82**	**16.1**	**2.02**	**0.14**	**24.0**
	Percent by category	24.2%	66.8%	8.4%	0.6%	100.0%
Tap Al wk wash						
33	Production of reusable drinking container (20 oz aluminum, 1 yr use)	11.6	3.43	0	0	15.0
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	0.022	0.11	0	0	0.13
	Production of secondary packaging	0	0	0	0	0
	Water processing (tap)	1.6E-04	0.30	0	0	0.30
	Filling (reusable drinking container filled once daily)	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (once/week, high water use)	0	3.96	0	0	3.96
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.016	0	0	0.016
	Chilling (none)	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	0.0032	3.59	0.27	3.87
	End of life management - caps & closures	0	-0.0034	0.45	0	0.45
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0	0
	TOTAL	**11.6**	**7.81**	**4.04**	**0.27**	**23.8**
	Percent by category	49.0%	32.9%	17.0%	1.1%	100.0%

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios (pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
Tap Al low wash						
34	Production of reusable drinking container (20 oz aluminum, 1 yr use)	11.6	3.43	0	0	15.0
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	0.022	0.11	0	0	0.13
	Production of secondary packaging	0	0	0	0	0
	Water processing (tap)	1.8E-04	0.33	0	0	0.33
	Filling (reusable drinking container filled once daily)	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, low water use)	0	16.8	0	0	16.8
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.032	0	0	0.032
	Chilling (none)	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	0.0032	3.59	0.27	3.87
	End of life management - caps & closures	0	-0.0034	0.45	0	0.45
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0	0
	TOTAL	**11.6**	**20.7**	**4.04**	**0.27**	**36.6**
	Percent by category	31.8%	56.5%	11.0%	0.7%	100.0%
Tap Al 1/2 full wash						
35	Production of reusable drinking container (20 oz aluminum, 1 yr use)	11.6	3.43	0	0	15.0
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	0.022	0.11	0	0	0.13
	Production of secondary packaging	0	0	0	0	0
	Water processing (tap)	3.7E-04	0.70	0	0	0.70
	Filling (reusable drinking container filled once daily)	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (high water, half full load)	0	55.5	0	0	55.5
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.22	0	0	0.22
	Chilling (none)	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	0.0032	3.59	0.27	3.87
	End of life management - caps & closures	0	-0.0034	0.45	0	0.45
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0	0
	TOTAL	**11.6**	**59.9**	**4.04**	**0.27**	**75.9**
	Percent by category	15.3%	79.0%	5.3%	0.4%	100.0%
Tap Al ice						
36	Production of reusable drinking container (20 oz aluminum, 1 yr use)	11.6	3.43	0	0	15.0
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	0.022	0.11	0	0	0.13
	Production of secondary packaging	0	0	0	0	0
	Water processing (tap)	3.3E-04	0.61	0	0	0.61
	Filling (reusable drinking container filled once daily)	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	27.7	0	0	27.7
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.11	0	0	0.11
	Chilling (50% ice)	0	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	0.0032	3.59	0.27	3.87
	End of life management - caps & closures	0	-0.0034	0.45	0	0.45
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0	0
	TOTAL	**11.6**	**32.0**	**4.04**	**0.27**	**48.0**
	Percent by category	24.3%	66.7%	8.4%	0.6%	100.0%

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios
(pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
Tap best						
37	Production of reusable drinking container (32 oz PET, used 5 yrs)	0.011	0.065	0	0	0.075
	Production of HOD bottle	0	0	0	0	0
	Production of caps, closures	0.0020	0.0099	0	0	0.012
	Production of secondary packaging	0	0	0	0	0
	Water processing (tap)	1.4E-04	0.27	0	0	0.27
	Filling (reusable drinking container filled twice daily)	0	0	0	0	0
	Distribution of filled containers	0	0	0	0	0
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (once/wk, low water)	0	0.75	0	0	0.75
	Industrial washing of HOD container	0	0	0	0	0
	Wastewater treatment	0	0.0014	0	0	0.0014
	Chilling (none)	0	0	0	0	0
	End of life management - drinking containers @ 100% recycling	0	-9.4E-04	0.23	0	0.23
	End of life management - caps & closures	0	-3.1E-04	0.040	0	0.040
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 3)	0	0	0	0	0
	TOTAL	**0.013**	**1.09**	**0.27**	**0**	**1.38**
	Percent by category	0.9%	79.2%	19.9%	0.0%	100.0%
HOD ref						
38	Production of reusable drinking container (20 oz aluminum, 1 yr use)	11.6	3.43	0	0	15.0
	Production of HOD bottle (Polycarb, 40 uses)	0.28	3.63	0	0	3.91
	Production of caps, closures	0.19	1.53	0	0	1.72
	Production of secondary packaging	0	0	0	0	0
	Water processing (purified municipal)	3.7E-04	10.6	0	0	10.6
	Filling (reusable drinking container filled once daily)	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi dist, 75 mi route)	0	3.70	0	0	3.70
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	27.7	0	0	27.7
	Industrial washing of HOD container	4.7E-04	2.43	0	0	2.43
	Wastewater treatment	0	0.15	0	0	0.15
	Chilling (HOD chiller unit)	0	35.7	0	0	35.7
	End of life management - HOD 100% recycling, container 0%	0	0.20	7.43	0.27	7.90
	End of life management - caps & closures	0	-0.047	6.18	0	6.14
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	-0.11	-1.04	0	0	-1.15
	TOTAL	**12.0**	**88.5**	**13.6**	**0.27**	**114**
	Percent by category	10.5%	77.4%	11.9%	0.2%	100.0%
HOD PET						
39	Production of reusable drinking container (20 oz aluminum, 1 yr use)	11.6	3.43	0	0	15.0
	Production of HOD bottle (PET, 40 uses)	0.35	2.13	0	0	2.48
	Production of caps, closures	0.19	1.53	0	0	1.72
	Production of secondary packaging	0	0	0	0	0
	Water processing (purified municipal)	3.7E-04	10.6	0	0	10.6
	Filling (reusable drinking container filled once daily)	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi dist, 75 mi route)	0	3.70	0	0	3.70
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	27.7	0	0	27.7
	Industrial washing of HOD container	4.7E-04	2.43	0	0	2.43
	Wastewater treatment	0	0.15	0	0	0.15
	Chilling (HOD chiller unit)	0	35.7	0	0	35.7
	End of life management - HOD 100% recycling, container 0%	0	0.21	7.43	0.27	7.91
	End of life management - caps & closures	0	-0.047	6.18	0	6.14
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	-0.14	-0.44	0	0	-0.58
	TOTAL	**12.0**	**87.6**	**13.6**	**0.27**	**114**
	Percent by category	10.6%	77.2%	12.0%	0.2%	100.0%

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios (pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
HOD heavy						
40	Production of reusable drinking container (20 oz aluminum, 1 yr use)	11.6	3.43	0	0	15.0
	Production of HOD bottle (Polycarb 10% heavier, 40 uses)	0.31	3.99	0	0	4.30
	Production of caps, closures	0.19	1.53	0	0	1.72
	Production of secondary packaging	0	0	0	0	0
	Water processing (purified municipal)	3.7E-04	10.6	0	0	10.6
	Filling (reusable drinking container filled once daily)	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi dist, 75 mi route)	0	3.71	0	0	3.71
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	27.7	0	0	27.7
	Industrial washing of HOD container	4.7E-04	2.43	0	0	2.43
	Wastewater treatment	0	0.15	0	0	0.15
	Chilling (HOD chiller unit)	0	35.7	0	0	35.7
	End of life management - HOD 100% recycling, container 0%	0	0.22	7.82	0.27	8.30
	End of life management - caps & closures	0	-0.047	6.18	0	6.14
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	-0.12	-1.15	0	0	-1.27
	TOTAL	**12.0**	**88.8**	**14.0**	**0.27**	**115**
	Percent by category	10.4%	77.2%	12.2%	0.2%	100.0%
HOD 30 trip						
41	Production of reusable drinking container (20 oz aluminum, 1 yr use)	11.6	3.43	0	0	15.0
	Production of HOD bottle (Polycarb, 30 uses)	0.38	4.84	0	0	5.22
	Production of caps, closures	0.19	1.53	0	0	1.72
	Production of secondary packaging	0	0	0	0	0
	Water processing (purified municipal)	3.7E-04	10.6	0	0	10.6
	Filling (reusable drinking container filled once daily)	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi dist, 75 mi route)	0	3.70	0	0	3.70
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	27.7	0	0	27.7
	Industrial washing of HOD container	4.7E-04	2.43	0	0	2.43
	Wastewater treatment	0	0.15	0	0	0.15
	Chilling (HOD chiller unit)	0	35.7	0	0	35.7
	End of life management - HOD 100% recycling, container 0%	0	0.26	8.71	0.27	9.24
	End of life management - caps & closures	0	-0.047	6.18	0	6.14
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	-0.15	-1.39	0	0	-1.54
	TOTAL	**12.0**	**89.4**	**14.9**	**0.27**	**117**
	Percent by category	10.3%	76.7%	12.8%	0.2%	100.0%
HOD nat						
42	Production of reusable drinking container (20 oz aluminum, 1 yr use)	11.6	3.43	0	0	15.0
	Production of HOD bottle (Polycarb, 40 uses)	0.28	3.63	0	0	3.91
	Production of caps, closures	0.19	1.53	0	0	1.72
	Production of secondary packaging	0	0	0	0	0
	Water processing (natural)	1.3E-04	5.22	0	0	5.22
	Filling (reusable drinking container filled once daily)	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi dist, 75 mi route)	0	3.70	0	0	3.70
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	27.7	0	0	27.7
	Industrial washing of HOD container	4.7E-04	2.43	0	0	2.43
	Wastewater treatment	0	0.12	0	0	0.12
	Chilling (HOD chiller unit)	0	35.7	0	0	35.7
	End of life management - HOD 100% recycling, container 0%	0	0.20	7.43	0.27	7.90
	End of life management - caps & closures	0	-0.047	6.18	0	6.14
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	-0.11	-1.04	0	0	-1.15
	TOTAL	**12.0**	**83.0**	**13.6**	**0.27**	**109**
	Percent by category	11.0%	76.3%	12.5%	0.2%	100.0%

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios
(pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
HOD 200 mi distrib						
43	Production of reusable drinking container (20 oz aluminum, 1 yr use)	11.6	3.43	0	0	15.0
	Production of HOD bottle (Polycarb, 40 uses)	0.28	3.63	0	0	3.91
	Production of caps, closures	0.19	1.53	0	0	1.72
	Production of secondary packaging	0	0	0	0	0
	Water processing (purified municipal)	3.7E-04	10.6	0	0	10.6
	Filling (reusable drinking container filled once daily)	0	0.40	0	0	0.40
	Distribution of filled containers (200 mi dist, 75 mi route)	0	6.33	0	0	6.33
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	27.7	0	0	27.7
	Industrial washing of HOD container	4.7E-04	2.43	0	0	2.43
	Wastewater treatment	0	0.15	0	0	0.15
	Chilling (HOD chiller unit)	0	35.7	0	0	35.7
	End of life management - HOD 100% recycling, container 0%	0	0.20	7.43	0.27	7.90
	End of life management - caps & closures	0	-0.047	6.18	0	6.14
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	-0.11	-1.04	0	0	-1.15
	TOTAL	**12.0**	**91.1**	**13.6**	**0.27**	**117**
	Percent by category	10.2%	77.9%	11.6%	0.2%	100.0%
HOD 50 mi route						
44	Production of reusable drinking container (20 oz aluminum, 1 yr use)	11.6	3.43	0	0	15.0
	Production of HOD bottle (Polycarb, 40 uses)	0.28	3.63	0	0	3.91
	Production of caps, closures	0.19	1.53	0	0	1.72
	Production of secondary packaging	0	0	0	0	0
	Water processing (purified municipal)	3.7E-04	10.6	0	0	10.6
	Filling (reusable drinking container filled once daily)	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi dist, 50 mi route)	0	2.76	0	0	2.76
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	27.7	0	0	27.7
	Industrial washing of HOD container	4.7E-04	2.43	0	0	2.43
	Wastewater treatment	0	0.15	0	0	0.15
	Chilling (HOD chiller unit)	0	35.7	0	0	35.7
	End of life management - HOD 100% recycling, container 0%	0	0.20	7.43	0.27	7.90
	End of life management - caps & closures	0	-0.047	6.18	0	6.14
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	-0.11	-1.04	0	0	-1.15
	TOTAL	**12.0**	**87.6**	**13.6**	**0.27**	**113**
	Percent by category	10.6%	77.2%	12.0%	0.2%	100.0%
HOD low chill						
45	Production of reusable drinking container (20 oz aluminum, 1 yr use)	11.6	3.43	0	0	15.0
	Production of HOD bottle (Polycarb, 40 uses)	0.28	3.63	0	0	3.91
	Production of caps, closures	0.19	1.53	0	0	1.72
	Production of secondary packaging	0	0	0	0	0
	Water processing (purified municipal)	3.7E-04	10.6	0	0	10.6
	Filling (reusable drinking container filled once daily)	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi dist, 75 mi route)	0	3.70	0	0	3.70
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	27.7	0	0	27.7
	Industrial washing of HOD container	4.7E-04	2.43	0	0	2.43
	Wastewater treatment	0	0.15	0	0	0.15
	Chilling (faster consumption = shorter chilling)	0	23.8	0	0	23.8
	End of life management - HOD 100% recycling, container 0%	0	0.20	7.43	0.27	7.90
	End of life management - caps & closures	0	-0.047	6.18	0	6.14
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	-0.11	-1.04	0	0	-1.15
	TOTAL	**12.0**	**76.6**	**13.6**	**0.27**	**102**
	Percent by category	11.7%	74.8%	13.3%	0.3%	100.0%

Table 2-12. Weight of Solid Waste for Drinking Water Scenarios
(pounds per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Landfilled Postconsumer Waste	Combusted Postconsumer Waste	TOTAL LB SW
HOD high chill						
46	Production of reusable drinking container (20 oz aluminum, 1 yr use)	11.6	3.43	0	0	15.0
	Production of HOD bottle (Polycarb, 40 uses)	0.28	3.63	0	0	3.91
	Production of caps, closures	0.19	1.53	0	0	1.72
	Production of secondary packaging	0	0	0	0	0
	Water processing (purified municipal)	3.7E-04	10.6	0	0	10.6
	Filling (reusable drinking container filled once daily)	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi dist, 75 mi route)	0	3.70	0	0	3.70
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	27.7	0	0	27.7
	Industrial washing of HOD container	4.7E-04	2.43	0	0	2.43
	Wastewater treatment	0	0.15	0	0	0.15
	Chilling (higher energy use)	0	42.9	0	0	42.9
	End of life management - HOD 100% recycling, container 0%	0	0.20	7.43	0.27	7.90
	End of life management - caps & closures	0	-0.047	6.18	0	6.14
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	-0.11	-1.04	0	0	-1.15
	TOTAL	**12.0**	**95.7**	**13.6**	**0.27**	**122**
	Percent by category	9.9%	78.7%	11.2%	0.2%	100.0%
HOD best						
47	Production of reusable drinking container (32 oz PET, used 5 yrs)	0.011	0.065	0	0	0.075
	Production of HOD bottle (Polycarb, 40 uses)	0.28	3.63	0	0	3.91
	Production of caps, closures	0.17	1.43	0	0	1.60
	Production of secondary packaging	0	0	0	0	0
	Water processing (natural)	1.4E-05	0.027	0	0	0.027
	Filling (reusable drinking container filled twice daily)	0	0.40	0	0	0.40
	Distribution of filled containers (50 mi dist, 50 mi route)	0	2.76	0	0	2.76
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (once/wk, low water use)	0	0.75	0	0	0.75
	Industrial washing of HOD container	4.7E-04	2.43	0	0	2.43
	Wastewater treatment	0	0.010	0	0	0.010
	Chilling (faster consumption = shorter chilling)	0	23.8	0	0	23.8
	End of life management - HOD 100% recycling, container 100%	0	0.44	0.23	0	0.67
	End of life management - caps & closures	0	-0.044	5.78	0	5.73
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 3)	-0.22	-2.08	0	0	-2.31
	TOTAL	**0.24**	**33.6**	**6.01**	**0**	**39.9**
	Percent by category	0.6%	84.3%	15.1%	0.0%	100.0%
HOD worst						
48	Production of reusable drinking container (16 oz drinking glass)	0.54	0.31	0	0	0.85
	Production of HOD bottle (PET 10% heavier, 30 uses)	0.51	3.13	0	0	3.63
	Production of caps, closures	0.16	1.42	0	0	1.59
	Production of secondary packaging	0	0	0	0	0
	Water processing (purified municipal)	5.4E-04	11.0	0	0	11.0
	Filling (reusable drinking container filled once daily)	0	0.40	0	0	0.40
	Distribution of filled containers (200 mi dist, 100 mi route)	0	7.29	0	0	7.29
	Consumer transport	0	0	0	0	0
	Home washing of reusable drinking container (high water use, half full load	0	69.4	0	0	69.4
	Industrial washing of HOD container	4.7E-04	2.43	0	0	2.43
	Wastewater treatment	0	0.32	0	0	0.32
	Chilling (higher energy use)	0	42.9	0	0	42.9
	End of life management - HOD 100% recycling, container 0%	0	0.30	16.6	0.83	17.8
	End of life management - caps & closures	0	-0.043	5.74	0	5.69
	End of life management - secondary packaging	0	0	0	0	0
	Credit for recycling (method 1)	-0.21	-0.64	0	0	-0.85
	TOTAL	**1.00**	**138**	**22.4**	**0.83**	**162**
	Percent by category	0.6%	85.1%	13.8%	0.5%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios
(cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
PET ref R1					
1	Production of PET bottle	0.16	0.83	0	0.99
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.025	0.12	0	0.15
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.017	0	0.017
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.14	0.069	10.8	11.0
	End of life management - caps & closures	0	-0.0038	1.89	1.89
	End of life management - secondary packaging	0	-0.0092	1.52	1.51
	Credit for recycling (method 1)	-0.020	-0.24	0	-0.25
	TOTAL	**0.37**	**1.18**	**14.2**	**15.8**
	Percent by category	2.3%	7.5%	90.2%	100.0%
PET ref R2					
2	Production of PET bottle	0.16	0.83	0	0.99
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.025	0.12	0	0.15
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.017	0	0.017
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0	-0.0063	5.96	5.96
	End of life management - caps & closures	0	-0.0038	1.89	1.89
	End of life management - secondary packaging	0	-0.0061	1.13	1.12
	Credit for recycling (method 2)	0	0	0	0
	TOTAL	**0.25**	**1.35**	**8.98**	**10.6**
	Percent by category	2.4%	12.7%	84.9%	100.0%
PET ref R3					
3	Production of PET bottle	0.16	0.83	0	0.99
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.025	0.12	0	0.15
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.017	0	0.017
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.28	0.15	5.96	6.39
	End of life management - caps & closures	0	-0.0038	1.89	1.89
	End of life management - secondary packaging	0	-0.0057	1.13	1.12
	Credit for recycling (method 3)	-0.039	-0.46	0	-0.50
	TOTAL	**0.49**	**1.04**	**8.98**	**10.5**
	Percent by category	4.6%	9.9%	85.5%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios (cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
PET 1 liter					
4	Production of PET bottle (1 liter)	0.23	1.23	0	1.46
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.022	0.11	0	0.13
	Production of secondary packaging	0.033	0.076	0	0.11
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.018	0	0.018
	Consumer transport (4% allocated to water)	0	0.011	0	0.011
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.20	0.10	15.9	16.2
	End of life management - caps & closures	0	-0.0033	1.65	1.65
	End of life management - secondary packaging	0	-0.0046	0.76	0.76
	Credit for recycling (method 1)	-0.0098	-0.30	0	-0.31
	TOTAL	**0.48**	**1.44**	**18.3**	**20.3**
	Percent by category	2.4%	7.1%	90.5%	100.0%
PET 8 oz					
5	Production of PET bottle (8 oz)	0.31	1.63	0	1.94
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.046	0.22	0	0.27
	Production of secondary packaging	0.14	0.32	0	0.46
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.018	0	0.018
	Consumer transport (4% allocated to water)	0	0.046	0	0.046
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.27	0.13	21.2	21.6
	End of life management - caps & closures	0	-0.0070	3.49	3.49
	End of life management - secondary packaging	0	-0.019	3.22	3.20
	Credit for recycling (method 1)	-0.042	-0.47	0	-0.51
	TOTAL	**0.72**	**2.10**	**27.9**	**30.7**
	Percent by category	2.4%	6.8%	90.8%	100.0%
PET light					
6	Production of PET bottle (lightweighted)	0.12	0.61	0	0.73
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.022	0.11	0	0.13
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.017	0	0.017
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.10	0.051	7.98	8.13
	End of life management - caps & closures	0	-0.0033	1.65	1.65
	End of life management - secondary packaging	0	-0.0092	1.52	1.51
	Credit for recycling (method 1)	-0.020	-0.18	0	-0.20
	TOTAL	**0.29**	**0.98**	**11.2**	**12.4**
	Percent by category	2.3%	7.9%	89.8%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios
(cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
PET light, low mold					
7	Production of PET bottle (lightweight, lower molding energy)	0.12	0.59	0	0.70
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.022	0.11	0	0.13
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.017	0	0.017
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.10	0.051	7.98	8.13
	End of life management - caps & closures	0	-0.0033	1.65	1.65
	End of life management - secondary packaging	0	-0.0092	1.52	1.51
	Credit for recycling (method 1)	-0.020	-0.18	0	-0.20
	TOTAL	**0.29**	**0.96**	**11.2**	**12.4**
	Percent by category	2.3%	7.7%	90.0%	100.0%
25% rPET R1					
8	Production of PET bottle (25% recycled content)	0.19	0.81	0	1.00
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.025	0.12	0	0.15
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.017	0	0.017
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.14	0.070	9.48	9.68
	End of life management - caps & closures	0	-0.0038	1.89	1.89
	End of life management - secondary packaging	0	-0.0092	1.52	1.51
	Credit for recycling (method 1)	-0.020	-0.21	0	-0.23
	TOTAL	**0.40**	**1.18**	**12.9**	**14.5**
	Percent by category	2.8%	8.2%	89.0%	100.0%
25% rPET R2					
9	Production of PET bottle (25% recycled content)	0.23	0.78	0	1.01
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.025	0.12	0	0.15
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.017	0	0.017
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0	-0.0063	5.96	5.96
	End of life management - caps & closures	0	-0.0038	1.89	1.89
	End of life management - secondary packaging	0	-0.0061	1.13	1.12
	Credit for recycling (method 2)	0	0	0	0
	TOTAL	**0.32**	**1.29**	**8.98**	**10.6**
	Percent by category	3.0%	12.2%	84.8%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios
(cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
25% rPET R3					
10	Production of PET bottle (25% recycled content)	0.16	0.83	0	0.99
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.025	0.12	0	0.15
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.017	0	0.017
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.28	0.15	5.96	6.39
	End of life management - caps & closures	0	-0.0038	1.89	1.89
	End of life management - secondary packaging	0	-0.0057	1.13	1.12
	Credit for recycling (method 3)	-0.039	-0.46	0	-0.50
	TOTAL	**0.49**	**1.04**	**8.98**	**10.5**
	Percent by category	4.6%	9.9%	85.5%	100.0%
PLA 0 decomp					
11	Production of PLA bottle	0.048	1.17	0	1.22
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.025	0.12	0	0.15
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.017	0	0.017
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 0% decomposition	0	-0.013	16.2	16.2
	End of life management - caps & closures	0	-0.0038	1.89	1.89
	End of life management - secondary packaging	0	-0.0092	1.52	1.51
	Credit for recycling (method 1)	-0.020	-0.043	0	-0.062
	TOTAL	**0.12**	**0.90**	**19.6**	**20.6**
	Percent by category	0.6%	4.4%	95.1%	100.0%
PLA 100 decomp					
12	Production of PLA bottle	0.048	1.17	0	1.22
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.025	0.12	0	0.15
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.017	0	0.017
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 100% decomposition	0	-0.17	16.2	16.0
	End of life management - caps & closures	0	-0.0038	1.89	1.89
	End of life management - secondary packaging	0	-0.0092	1.52	1.51
	Credit for recycling (method 1)	-0.020	-0.043	0	-0.062
	TOTAL	**0.12**	**0.74**	**19.6**	**20.5**
	Percent by category	0.6%	3.6%	95.8%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios
(cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
PLA compost					
13	Production of PLA bottle	0.048	1.17	0	1.22
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.025	0.12	0	0.15
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.017	0	0.017
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 100% composting	0.23	-0.014	0	0.22
	End of life management - caps & closures	0	-0.0038	1.89	1.89
	End of life management - secondary packaging	0	-0.0092	1.52	1.51
	Credit for recycling (method 1)	-0.020	-0.043	0	-0.062
	TOTAL	**0.35**	**0.90**	**3.41**	**4.66**
	Percent by category	7.5%	19.3%	73.2%	100.0%
PET nat					
14	Production of PET bottle	0.16	0.83	0	0.99
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.025	0.12	0	0.15
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (natural)	0	0.10	0	0.10
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (130 mi)	0	0.045	0	0.045
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0	0	0
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.14	0.069	10.8	11.0
	End of life management - caps & closures	0	-0.0038	1.89	1.89
	End of life management - secondary packaging	0	-0.0092	1.52	1.51
	Credit for recycling (method 1)	-0.020	-0.24	0	-0.25
	TOTAL	**0.37**	**1.10**	**14.2**	**15.7**
	Percent by category	2.3%	7.0%	90.6%	100.0%
PET Maine nat					
15	Production of PET bottle	0.16	0.94	0	1.10
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.025	0.12	0	0.15
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (natural)	0	0.13	0	0.13
	Filling	0	0.010	0	0.010
	Distribution of filled containers from Maine	0	1.14	0	1.14
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0	0	0
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.14	0.069	10.8	11.0
	End of life management - caps & closures	0	-0.0038	1.89	1.89
	End of life management - secondary packaging	0	-0.0092	1.52	1.51
	Credit for recycling (method 1)	-0.020	-0.24	0	-0.25
	TOTAL	**0.37**	**2.34**	**14.2**	**16.9**
	Percent by category	2.2%	13.8%	84.0%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios
(cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
PET Fiji nat					
16	Production of PET bottle	0.33	1.95	0	2.27
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.040	0.20	0	0.24
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (natural)	0	1.9E-04	0	1.9E-04
	Filling	0	0.010	0	0.010
	Distribution of filled containers from Fiji	0	0.67	0	0.67
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0	0	0
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.28	0.14	22.4	22.8
	End of life management - caps & closures	0	-0.0061	3.07	3.06
	End of life management - secondary packaging	0	-0.0092	1.52	1.51
	Credit for recycling (method 1)	-0.020	-0.44	0	-0.46
	TOTAL	**0.70**	**2.68**	**27.0**	**30.4**
	Percent by category	2.3%	8.8%	88.9%	100.0%
PET Fiji free sea					
17	Production of PET bottle	0.33	1.95	0	2.27
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.040	0.20	0	0.24
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (natural)	0	1.9E-04	0	1.9E-04
	Filling	0	0.010	0	0.010
	Distribution of filled containers from Fiji (discounted ocean)	0	0.33	0	0.33
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0	0	0
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.28	0.14	22.4	22.8
	End of life management - caps & closures	0	-0.0061	3.07	3.06
	End of life management - secondary packaging	0	-0.0092	1.52	1.51
	Credit for recycling (method 1)	-0.020	-0.44	0	-0.46
	TOTAL	**0.70**	**2.35**	**27.0**	**30.0**
	Percent by category	2.3%	7.8%	89.9%	100.0%
Glass France					
18	Production of glass bottle	5.11	2.03	0	7.14
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.29	1.43	0	1.72
	Production of secondary packaging	0.093	0.21	0	0.30
	Water processing (natural)	0	0.069	0	0.069
	Filling	0	0.0055	0	0.0055
	Distribution of filled containers from France	0	1.73	0	1.73
	Consumer transport (4% allocated to water)	0	0.030	0	0.030
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0	0	0
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 74% recycling	0	0.29	36.8	37.1
	End of life management - caps & closures	0	-0.044	22.3	22.2
	End of life management - secondary packaging	0	-0.013	2.13	2.11
	Credit for recycling (method 1)	-1.92	-1.16	0	-3.08
	TOTAL	**3.58**	**4.58**	**61.2**	**69.4**
	Percent by category	5.2%	6.6%	88.2%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios
(cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
PET 500 mi empty					
19	Production of PET bottle (molded offsite)	0.16	0.87	0	1.03
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.025	0.12	0	0.15
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.017	0	0.017
	Consumer transport (4% allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.14	0.069	10.8	11.0
	End of life management - caps & closures	0	-0.0038	1.89	1.89
	End of life management - secondary packaging	0	-0.0092	1.52	1.51
	Credit for recycling (method 1)	-0.020	-0.24	0	-0.25
	TOTAL	**0.37**	**1.22**	**14.2**	**15.8**
	Percent by category	2.3%	7.7%	90.0%	100.0%
PET 100% store trip					
20	Production of PET bottle	0.16	0.83	0	0.99
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.025	0.12	0	0.15
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.017	0	0.017
	Consumer transport (100% of trip allocated to water)	0	0.54	0	0.54
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 62% recycling	0.14	0.069	10.8	11.0
	End of life management - caps & closures	0	-0.0038	1.89	1.89
	End of life management - secondary packaging	0	-0.0092	1.52	1.51
	Credit for recycling (method 1)	-0.020	-0.24	0	-0.25
	TOTAL	**0.37**	**1.70**	**14.2**	**16.3**
	Percent by category	2.3%	10.4%	87.3%	100.0%
PET refrig					
21	Production of PET bottle	0.16	0.83	0	0.99
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.025	0.12	0	0.15
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.017	0	0.017
	Consumer transport (4% of trip allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (3.5 days home refrig)	0	0.12	0	0.12
	End of life management - bottles @ 62% recycling	0.14	0.069	10.8	11.0
	End of life management - caps & closures	0	-0.0038	1.89	1.89
	End of life management - secondary packaging	0	-0.0092	1.52	1.51
	Credit for recycling (method 1)	-0.020	-0.24	0	-0.25
	TOTAL	**0.37**	**1.30**	**14.2**	**15.9**
	Percent by category	2.3%	8.2%	89.5%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios
(cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
PET 37%R					
22	Production of PET bottle	0.16	0.83	0	0.99
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.025	0.12	0	0.15
	Production of secondary packaging	0.066	0.15	0	0.22
	Water processing (purified municipal)	4.8E-06	0.21	0	0.21
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi)	0	0.017	0	0.017
	Consumer transport (4% of trip allocated to water)	0	0.022	0	0.022
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.8E-04	0	6.8E-04
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 37% recycling	0.082	0.034	12.8	12.9
	End of life management - caps & closures	0	-0.0038	1.89	1.89
	End of life management - secondary packaging	0	-0.0092	1.52	1.51
	Credit for recycling (method 1)	-0.020	-0.16	0	-0.18
	TOTAL	**0.31**	**1.23**	**16.2**	**17.7**
	Percent by category	1.8%	6.9%	91.3%	100.0%
PET best					
23	Production of PET bottle (lightweight, 25% recycl cont)	0.12	0.59	0	0.70
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.022	0.11	0	0.13
	Production of secondary packaging (film only)	0.015	0.041	0	0.056
	Water processing (natural)	0	1.5E-04	0	1.5E-04
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (20 mi)	0	0.0069	0	0.0069
	Consumer transport (0% of trip allocated to water)	0	1.5E-04	0	1.5E-04
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0	0	0
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 100% recycling	0.33	0.19	0	0.52
	End of life management - caps & closures	0	-0.0033	1.65	1.65
	End of life management - secondary packaging	0	-0.0042	0.91	0.91
	Credit for recycling (method 3)	0	-0.45	0	-0.45
	TOTAL	**0.48**	**0.48**	**2.56**	**3.53**
	Percent by category	13.6%	13.7%	72.7%	100.0%
PET worst					
24	Production of PET bottle (8 oz, molded off-site)	0.31	1.88	0	2.19
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.046	0.22	0	0.27
	Production of secondary packaging	0.15	0.35	0	0.50
	Water processing (natural)	0	0.14	0	0.14
	Filling	0	0.010	0	0.010
	Distribution of filled containers from Maine	0	1.18	0	1.18
	Consumer transport (100% of trip allocated to water)	0	1.14	0	1.14
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	2.7E-05	0	2.7E-05
	Chilling (1 wk home refrig)	0	0.49	0	0.49
	End of life management - bottles @ 0% recycling	0	-0.033	30.7	30.6
	End of life management - caps & closures	0	-0.0070	3.49	3.49
	End of life management - secondary packaging	0	-0.021	3.52	3.50
	Credit for recycling (method 1)	-0.045	-0.098	0	-0.14
	TOTAL	**0.46**	**5.26**	**37.7**	**43.4**
	Percent by category	1.1%	12.1%	86.8%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios
(cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
PLA best					
25	Production of PLA bottle	0.035	0.84	0	0.87
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0.022	0.11	0	0.13
	Production of secondary packaging (film only)	0.015	0.041	0	0.056
	Water processing (natural)	0	1.5E-04	0	1.5E-04
	Filling	0	0.0080	0	0.0080
	Distribution of filled containers (20 mi)	0	0.0069	0	0.0069
	Consumer transport (0% of trip allocated to water)	0	1.5E-04	0	1.5E-04
	Home washing of reusable drinking container	0	0	0	0
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0	0	0
	Chilling (none)	0	0	0	0
	End of life management - bottles @ 0% decomposition	0	-0.0095	11.9	11.9
	End of life management - caps & closures	0	-0.0033	1.65	1.65
	End of life management - secondary packaging	0	-0.0042	0.91	0.91
	Credit for recycling (method 3)	0	0	0	0
	TOTAL	**0.072**	**0.45**	**14.5**	**15.0**
	Percent by category	0.5%	3.0%	96.6%	100.0%
Tap Al ref					
26	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.23	0.069	0	0.30
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	4.5E-04	0.0022	0	0.0026
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	5.2E-06	0.0096	0	0.0096
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.55	0	0.55
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0.0022	0	0.0022
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	6.5E-05	0.39	0.39
	End of life management - caps & closures	0	-6.8E-05	0.034	0.034
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0
	TOTAL	**0.23**	**0.64**	**0.43**	**1.30**
	Percent by category	17.9%	49.1%	32.9%	100.0%
Tap PET					
27	Production of reusable drinking container (32 oz PET, 1 yr use)	0.0021	0.013	0	0.015
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	4.0E-04	0.0020	0	0.0024
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	4.3E-06	0.0080	0	0.0080
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.35	0	0.35
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0.0014	0	0.0014
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	-1.9E-04	0.18	0.18
	End of life management - caps & closures	0	-6.1E-05	0.031	0.031
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0
	TOTAL	**0.0025**	**0.37**	**0.21**	**0.58**
	Percent by category	0.4%	63.8%	35.8%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios
(cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
Tap steel					
28	Production of reusable drinking container (27 oz steel, 1 yr use)	0.038	0.032	0	0.070
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	9.7E-04	0.0048	0	0.0058
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	4.6E-06	0.0085	0	0.0085
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.41	0	0.41
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0.0016	0	0.0016
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	8.4E-05	0.30	0.30
	End of life management - caps & closures	0	-1.5E-04	0.075	0.074
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0
	TOTAL	**0.039**	**0.46**	**0.38**	**0.87**
	Percent by category	4.5%	52.4%	43.1%	100.0%
Tap glass					
29	Production of reusable drinking container (16 oz drinking glass, 1 yr use)	0.011	0.0062	0	0.017
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	0	0	0	0
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	5.8E-06	0.011	0	0.011
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.69	0	0.69
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0.0027	0	0.0027
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	5.6E-05	0.12	0.12
	End of life management - caps & closures	0	0	0	0
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0
	TOTAL	**0.011**	**0.71**	**0.12**	**0.85**
	Percent by category	1.3%	84.2%	14.5%	100.0%
Tap Al 5 yr					
30	Production of reusable drinking container (20 oz aluminum, 5 yrs use)	0.046	0.014	0	0.060
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	8.9E-05	4.4E-04	0	5.3E-04
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	5.2E-06	0.0096	0	0.0096
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.55	0	0.55
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0.0022	0	0.0022
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	1.3E-05	0.079	0.079
	End of life management - caps & closures	0	-1.4E-05	0.0068	0.0068
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0
	TOTAL	**0.047**	**0.58**	**0.085**	**0.71**
	Percent by category	6.5%	81.5%	12.0%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios
(cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
Tap Al 100%R					
31	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.23	0.069	0	0.30
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	4.5E-04	0.0022	0	0.0026
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	5.2E-06	0.0096	0	0.0096
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.55	0	0.55
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0.0022	0	0.0022
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 100% recycling	0.0033	0.0026	0.20	0.20
	End of life management - caps & closures	0	-6.8E-05	0.034	0.034
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	-0.12	-0.033	0	-0.15
	TOTAL	**0.12**	**0.61**	**0.23**	**0.96**
	Percent by category	12.5%	63.4%	24.1%	100.0%
Tap Al 2x fill					
32	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.12	0.034	0	0.15
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	2.2E-04	0.0011	0	0.0013
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	4.0E-06	0.0074	0	0.0074
	Filling (reusable drinking container filled twice daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.28	0	0.28
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0.0011	0	0.0011
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	3.2E-05	0.20	0.20
	End of life management - caps & closures	0	-3.4E-05	0.017	0.017
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0
	TOTAL	**0.12**	**0.32**	**0.21**	**0.65**
	Percent by category	17.9%	49.3%	32.8%	100.0%
Tap Al wk wash					
33	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.23	0.069	0	0.30
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	4.5E-04	0.0022	0	0.0026
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	3.2E-06	0.0059	0	0.0059
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (once/week, high water use)	0	0.079	0	0.079
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	3.1E-04	0	3.1E-04
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	6.5E-05	0.39	0.39
	End of life management - caps & closures	0	-6.8E-05	0.034	0.034
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0
	TOTAL	**0.23**	**0.16**	**0.43**	**0.82**
	Percent by category	28.5%	19.1%	52.4%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios
(cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
Tap Al low wash					
34	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.23	0.069	0	0.30
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	4.5E-04	0.0022	0	0.0026
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	3.5E-06	0.0065	0	0.0065
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, low water use)	0	0.34	0	0.34
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	6.3E-04	0	6.3E-04
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	6.5E-05	0.39	0.39
	End of life management - caps & closures	0	-6.8E-05	0.034	0.034
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0
	TOTAL	**0.23**	**0.41**	**0.43**	**1.07**
	Percent by category	21.7%	38.5%	39.8%	100.0%
Tap Al 1/2 full wash					
35	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.23	0.069	0	0.30
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	4.5E-04	0.0022	0	0.0026
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	7.5E-06	0.014	0	0.014
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (high water, half full load)	0	1.11	0	1.11
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0.0044	0	0.0044
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	6.5E-05	0.39	0.39
	End of life management - caps & closures	0	-6.8E-05	0.034	0.034
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0
	TOTAL	**0.23**	**1.20**	**0.43**	**1.86**
	Percent by category	12.5%	64.5%	23.0%	100.0%
Tap Al ice					
36	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.23	0.069	0	0.30
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	4.5E-04	0.0022	0	0.0026
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	6.6E-06	0.012	0	0.012
	Filling (reusable drinking container filled once daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.55	0	0.55
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	0.0022	0	0.0022
	Chilling (50% ice)	0	0	0	0
	End of life management - drinking containers @ 0% recycling	0	6.5E-05	0.39	0.39
	End of life management - caps & closures	0	-6.8E-05	0.034	0.034
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	0	0	0	0
	TOTAL	**0.23**	**0.64**	**0.43**	**1.30**
	Percent by category	17.9%	49.2%	32.9%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios
(cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
Tap best					
37	Production of reusable drinking container (32 oz PET, used 5 yrs)	2.1E-04	0.0013	0	0.0015
	Production of HOD bottle	0	0	0	0
	Production of caps, closures	4.0E-05	2.0E-04	0	2.4E-04
	Production of secondary packaging	0	0	0	0
	Water processing (tap)	2.9E-06	0.0053	0	0.0054
	Filling (reusable drinking container filled twice daily)	0	0	0	0
	Distribution of filled containers	0	0	0	0
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (once/wk, low water)	0	0.015	0	0.015
	Industrial washing of HOD container	0	0	0	0
	Wastewater treatment	0	2.8E-05	0	2.8E-05
	Chilling (none)	0	0	0	0
	End of life management - drinking containers @ 100% recycling	0	-1.9E-05	0.018	0.018
	End of life management - caps & closures	0	-6.1E-06	0.0031	0.0031
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 3)	0	0	0	0
	TOTAL	**2.5E-04**	**0.022**	**0.021**	**0.043**
	Percent by category	0.6%	50.9%	48.5%	100.0%
HOD ref					
38	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.23	0.069	0	0.30
	Production of HOD bottle (Polycarb, 40 uses)	0.0056	0.073	0	0.078
	Production of caps, closures	0.0037	0.031	0	0.034
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	7.3E-06	0.21	0	0.21
	Filling (reusable drinking container filled once daily)	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi dist, 75 mi route)	0	0.074	0	0.074
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.55	0	0.55
	Industrial washing of HOD container	9.4E-06	0.049	0	0.049
	Wastewater treatment	0	0.0031	0	0.0031
	Chilling (HOD chiller unit)	0	0.71	0	0.71
	End of life management - HOD 100% recycling, container 0%	0	0.0039	0.69	0.69
	End of life management - caps & closures	0	-9.4E-04	0.47	0.47
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	-0.0022	-0.021	0	-0.023
	TOTAL	**0.24**	**1.77**	**1.16**	**3.17**
	Percent by category	7.6%	55.9%	36.5%	100.0%
HOD PET					
39	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.23	0.069	0	0.30
	Production of HOD bottle (PET, 40 uses)	0.0069	0.043	0	0.050
	Production of caps, closures	0.0037	0.031	0	0.034
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	7.3E-06	0.21	0	0.21
	Filling (reusable drinking container filled once daily)	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi dist, 75 mi route)	0	0.074	0	0.074
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.55	0	0.55
	Industrial washing of HOD container	9.4E-06	0.049	0	0.049
	Wastewater treatment	0	0.0031	0	0.0031
	Chilling (HOD chiller unit)	0	0.71	0	0.71
	End of life management - HOD 100% recycling, container 0%	0	0.0042	0.69	0.69
	End of life management - caps & closures	0	-9.4E-04	0.47	0.47
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	-0.0029	-0.0087	0	-0.012
	TOTAL	**0.24**	**1.75**	**1.16**	**3.15**
	Percent by category	7.6%	55.7%	36.7%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios
(cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
HOD heavy					
40	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.23	0.069	0	0.30
	Production of HOD bottle (Polycarb 10% heavier, 40 uses)	0.0062	0.080	0	0.086
	Production of caps, closures	0.0037	0.031	0	0.034
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	7.3E-06	0.21	0	0.21
	Filling (reusable drinking container filled once daily)	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi dist, 75 mi route)	0	0.074	0	0.074
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.55	0	0.55
	Industrial washing of HOD container	9.4E-06	0.049	0	0.049
	Wastewater treatment	0	0.0031	0	0.0031
	Chilling (HOD chiller unit)	0	0.71	0	0.71
	End of life management - HOD 100% recycling, container 0%	0	0.0043	0.71	0.72
	End of life management - caps & closures	0	-9.4E-04	0.47	0.47
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	-0.0024	-0.023	0	-0.025
	TOTAL	**0.24**	**1.78**	**1.19**	**3.20**
	Percent by category	7.5%	55.5%	37.0%	100.0%
HOD 30 trip					
41	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.23	0.069	0	0.30
	Production of HOD bottle (Polycarb, 30 uses)	0.0075	0.097	0	0.10
	Production of caps, closures	0.0037	0.031	0	0.034
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	7.3E-06	0.21	0	0.21
	Filling (reusable drinking container filled once daily)	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi dist, 75 mi route)	0	0.074	0	0.074
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.55	0	0.55
	Industrial washing of HOD container	9.4E-06	0.049	0	0.049
	Wastewater treatment	0	0.0031	0	0.0031
	Chilling (HOD chiller unit)	0	0.71	0	0.71
	End of life management - HOD 100% recycling, container 0%	0	0.0052	0.78	0.79
	End of life management - caps & closures	0	-9.4E-04	0.47	0.47
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	-0.0030	-0.028	0	-0.031
	TOTAL	**0.24**	**1.79**	**1.25**	**3.28**
	Percent by category	7.3%	54.5%	38.2%	100.0%
HOD nat					
42	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.23	0.069	0	0.30
	Production of HOD bottle (Polycarb, 40 uses)	0.0056	0.073	0	0.078
	Production of caps, closures	0.0037	0.031	0	0.034
	Production of secondary packaging	0	0	0	0
	Water processing (natural)	2.6E-06	0.10	0	0.10
	Filling (reusable drinking container filled once daily)	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi dist, 75 mi route)	0	0.074	0	0.074
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.55	0	0.55
	Industrial washing of HOD container	9.4E-06	0.049	0	0.049
	Wastewater treatment	0	0.0024	0	0.0024
	Chilling (HOD chiller unit)	0	0.71	0	0.71
	End of life management - HOD 100% recycling, container 0%	0	0.0039	0.69	0.69
	End of life management - caps & closures	0	-9.4E-04	0.47	0.47
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	-0.0022	-0.021	0	-0.023
	TOTAL	**0.24**	**1.66**	**1.16**	**3.06**
	Percent by category	7.8%	54.3%	37.8%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios
(cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
HOD 200 mi distrib					
43	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.23	0.069	0	0.30
	Production of HOD bottle (Polycarb, 40 uses)	0.0056	0.073	0	0.078
	Production of caps, closures	0.0037	0.031	0	0.034
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	7.3E-06	0.21	0	0.21
	Filling (reusable drinking container filled once daily)	0	0.0080	0	0.0080
	Distribution of filled containers (200 mi dist, 75 mi route)	0	0.13	0	0.13
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.55	0	0.55
	Industrial washing of HOD container	9.4E-06	0.049	0	0.049
	Wastewater treatment	0	0.0031	0	0.0031
	Chilling (HOD chiller unit)	0	0.71	0	0.71
	End of life management - HOD 100% recycling, container 0%	0	0.0039	0.69	0.69
	End of life management - caps & closures	0	-9.4E-04	0.47	0.47
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	-0.0022	-0.021	0	-0.023
	TOTAL	**0.24**	**1.82**	**1.16**	**3.22**
	Percent by category	7.4%	56.6%	35.9%	100.0%
HOD 50 mi route					
44	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.23	0.069	0	0.30
	Production of HOD bottle (Polycarb, 40 uses)	0.0056	0.073	0	0.078
	Production of caps, closures	0.0037	0.031	0	0.034
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	7.3E-06	0.21	0	0.21
	Filling (reusable drinking container filled once daily)	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi dist, 50 mi route)	0	0.055	0	0.055
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.55	0	0.55
	Industrial washing of HOD container	9.4E-06	0.049	0	0.049
	Wastewater treatment	0	0.0031	0	0.0031
	Chilling (HOD chiller unit)	0	0.71	0	0.71
	End of life management - HOD 100% recycling, container 0%	0	0.0039	0.69	0.69
	End of life management - caps & closures	0	-9.4E-04	0.47	0.47
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	-0.0022	-0.021	0	-0.023
	TOTAL	**0.24**	**1.75**	**1.16**	**3.15**
	Percent by category	7.6%	55.7%	36.7%	100.0%
HOD low chill					
45	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.23	0.069	0	0.30
	Production of HOD bottle (Polycarb, 40 uses)	0.0056	0.073	0	0.078
	Production of caps, closures	0.0037	0.031	0	0.034
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	7.3E-06	0.21	0	0.21
	Filling (reusable drinking container filled once daily)	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi dist, 75 mi route)	0	0.074	0	0.074
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.55	0	0.55
	Industrial washing of HOD container	9.4E-06	0.049	0	0.049
	Wastewater treatment	0	0.0031	0	0.0031
	Chilling (faster consumption = shorter chilling)	0	0.48	0	0.48
	End of life management - HOD 100% recycling, container 0%	0	0.0039	0.69	0.69
	End of life management - caps & closures	0	-9.4E-04	0.47	0.47
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	-0.0022	-0.021	0	-0.023
	TOTAL	**0.24**	**1.53**	**1.16**	**2.93**
	Percent by category	8.2%	52.3%	39.5%	100.0%

Table 2-13. Volume of Solid Waste for Drinking Water Scenarios
(cubic feet per 1,000 gallons)

		Process Solid Waste	Fuel Solid Waste	Postconsumer Solid Waste	TOTAL CU FT SW
HOD high chill					
46	Production of reusable drinking container (20 oz aluminum, 1 yr use)	0.23	0.069	0	0.30
	Production of HOD bottle (Polycarb, 40 uses)	0.0056	0.073	0	0.078
	Production of caps, closures	0.0037	0.031	0	0.034
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	7.3E-06	0.21	0	0.21
	Filling (reusable drinking container filled once daily)	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi dist, 75 mi route)	0	0.074	0	0.074
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (daily, high water use)	0	0.55	0	0.55
	Industrial washing of HOD container	9.4E-06	0.049	0	0.049
	Wastewater treatment	0	0.0031	0	0.0031
	Chilling (higher energy use)	0	0.86	0	0.86
	End of life management - HOD 100% recycling, container 0%	0	0.0039	0.69	0.69
	End of life management - caps & closures	0	-9.4E-04	0.47	0.47
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	-0.0022	-0.021	0	-0.023
	TOTAL	**0.24**	**1.91**	**1.16**	**3.31**
	Percent by category	7.2%	57.8%	34.9%	100.0%
HOD best					
47	Production of reusable drinking container (32 oz PET, used 5 yrs)	2.1E-04	0.0013	0	0.0015
	Production of HOD bottle (Polycarb, 40 uses)	0.0056	0.073	0	0.078
	Production of caps, closures	0.0033	0.029	0	0.032
	Production of secondary packaging	0	0	0	0
	Water processing (natural)	2.8E-07	5.3E-04	0	5.3E-04
	Filling (reusable drinking container filled twice daily)	0	0.0080	0	0.0080
	Distribution of filled containers (50 mi dist, 50 mi route)	0	0.055	0	0.055
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (once/wk, low water use)	0	0.015	0	0.015
	Industrial washing of HOD container	9.4E-06	0.049	0	0.049
	Wastewater treatment	0	2.1E-04	0	2.1E-04
	Chilling (faster consumption = shorter chilling)	0	0.48	0	0.48
	End of life management - HOD 100% recycling, container 100%	0	0.0088	0.018	0.027
	End of life management - caps & closures	0	-8.8E-04	0.44	0.44
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 3)	-0.0045	-0.042	0	-0.046
	TOTAL	**0.0047**	**0.67**	**0.46**	**1.13**
	Percent by category	0.4%	59.3%	40.3%	100.0%
HOD worst					
48	Production of reusable drinking container (16 oz drinking glass)	0.011	0.0062	0	0.017
	Production of HOD bottle (PET 10% heavier, 30 uses)	0.010	0.063	0	0.073
	Production of caps, closures	0.0033	0.028	0	0.032
	Production of secondary packaging	0	0	0	0
	Water processing (purified municipal)	1.1E-05	0.22	0	0.22
	Filling (reusable drinking container filled once daily)	0	0.0080	0	0.0080
	Distribution of filled containers (200 mi dist, 100 mi route)	0	0.15	0	0.15
	Consumer transport	0	0	0	0
	Home washing of reusable drinking container (high water use, half full load)	0	1.39	0	1.39
	Industrial washing of HOD container	9.4E-06	0.049	0	0.049
	Wastewater treatment	0	0.0063	0	0.0063
	Chilling (higher energy use)	0	0.86	0	0.86
	End of life management - HOD 100% recycling, container 0%	0	0.0061	0.55	0.56
	End of life management - caps & closures	0	-8.7E-04	0.44	0.44
	End of life management - secondary packaging	0	0	0	0
	Credit for recycling (method 1)	-0.0042	-0.013	0	-0.017
	TOTAL	**0.020**	**2.76**	**0.99**	**3.77**
	Percent by category	0.5%	73.3%	26.2%	100.0%

Figure 2-6. Solid Waste Results for Bottled Water Subscenarios (pounds per 1,000 gallons)

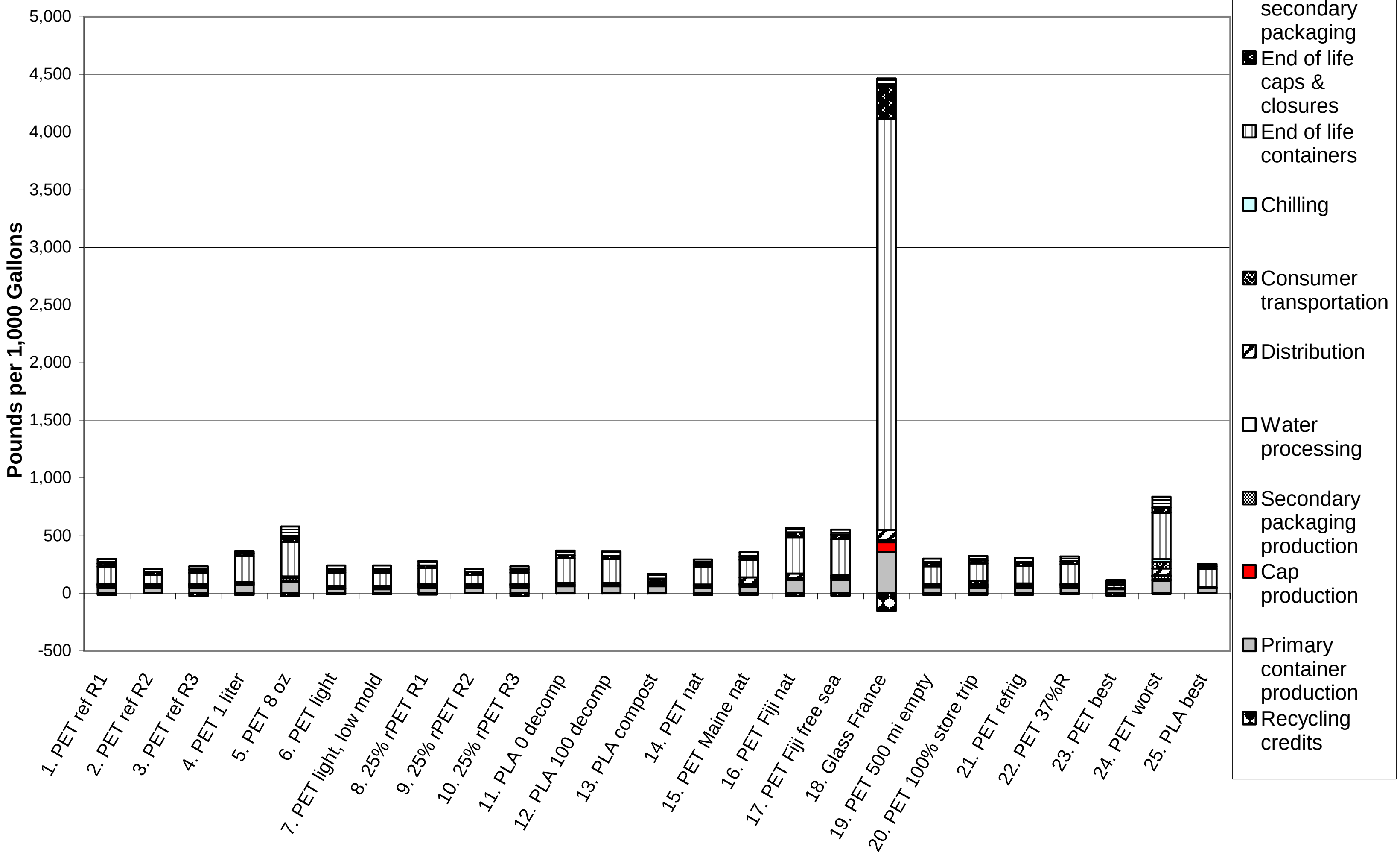
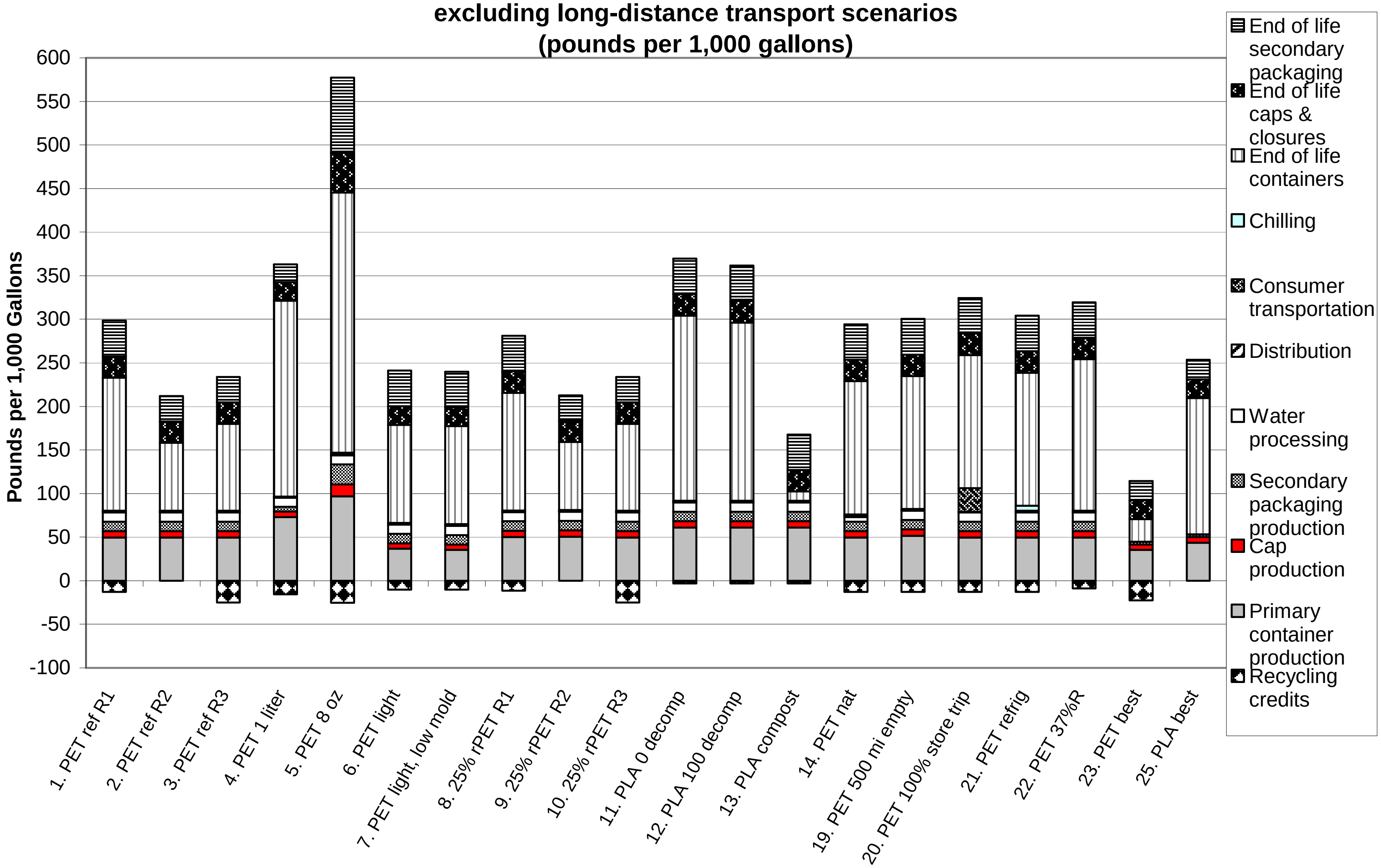


Figure 2-7. Solid Waste Results for Bottled Water Subscenarios excluding long-distance transport scenarios (pounds per 1,000 gallons)



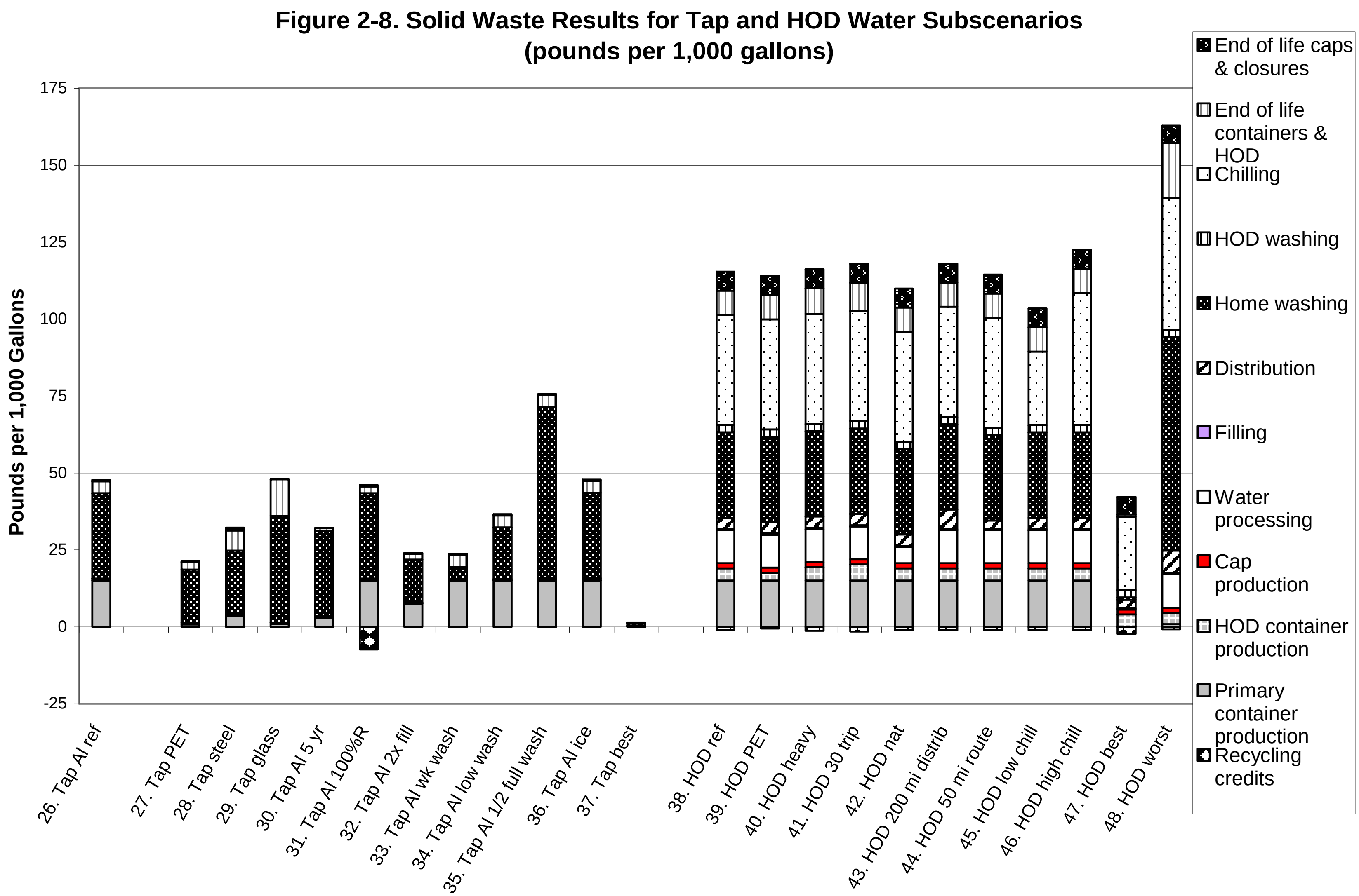


Figure 2-8. Solid Waste Results for Tap and HOD Water Subscenarios
(pounds per 1,000 gallons)
Pounds per 1,000 Gallons
175
150
125
100
75
50
25
0
-25
26. Tap Al ref
27. Tap PET
28. Tap steel
29. Tap glass
30. Tap Al 5 yr
31. Tap Al 100%R
32. Tap Al 2x fill
33. Tap Al wk wash
34. Tap Al low wash
35. Tap Al 1/2 full wash
36. Tap Al ice
37. Tap best
38. HOD ref
39. HOD PET
40. HOD heavy
41. HOD 30 trip
42. HOD nat
43. HOD 200 mi distrib
44. HOD 50 mi route
45. HOD low chill
46. HOD high chill
47. HOD best
48. HOD worst
End of life caps & closures
End of life containers & HOD
Chilling
HOD washing
Home washing
Distribution
Filling
Water processing
Cap production
HOD container production
Primary container production
Recycling credits

Figure 2-9. Solid Waste Volume Results for Bottled Water Subscenarios (compacted cubic feet per 1,000 gallons)

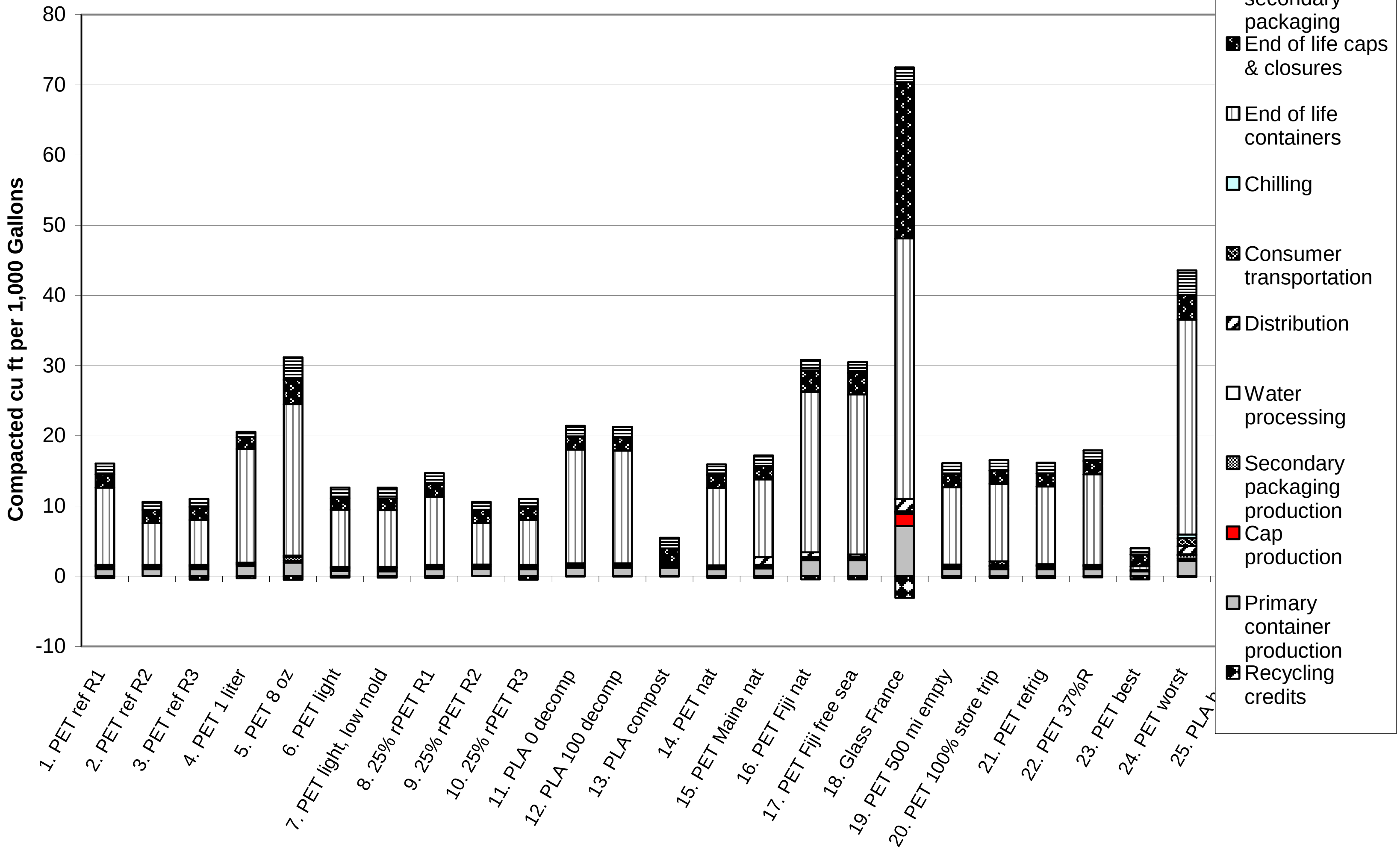


Figure 2-10. Solid Waste Volume Results for Bottled Water Subscenarios excluding long-distance transport scenarios (compacted cubic feet per 1,000 gallons)

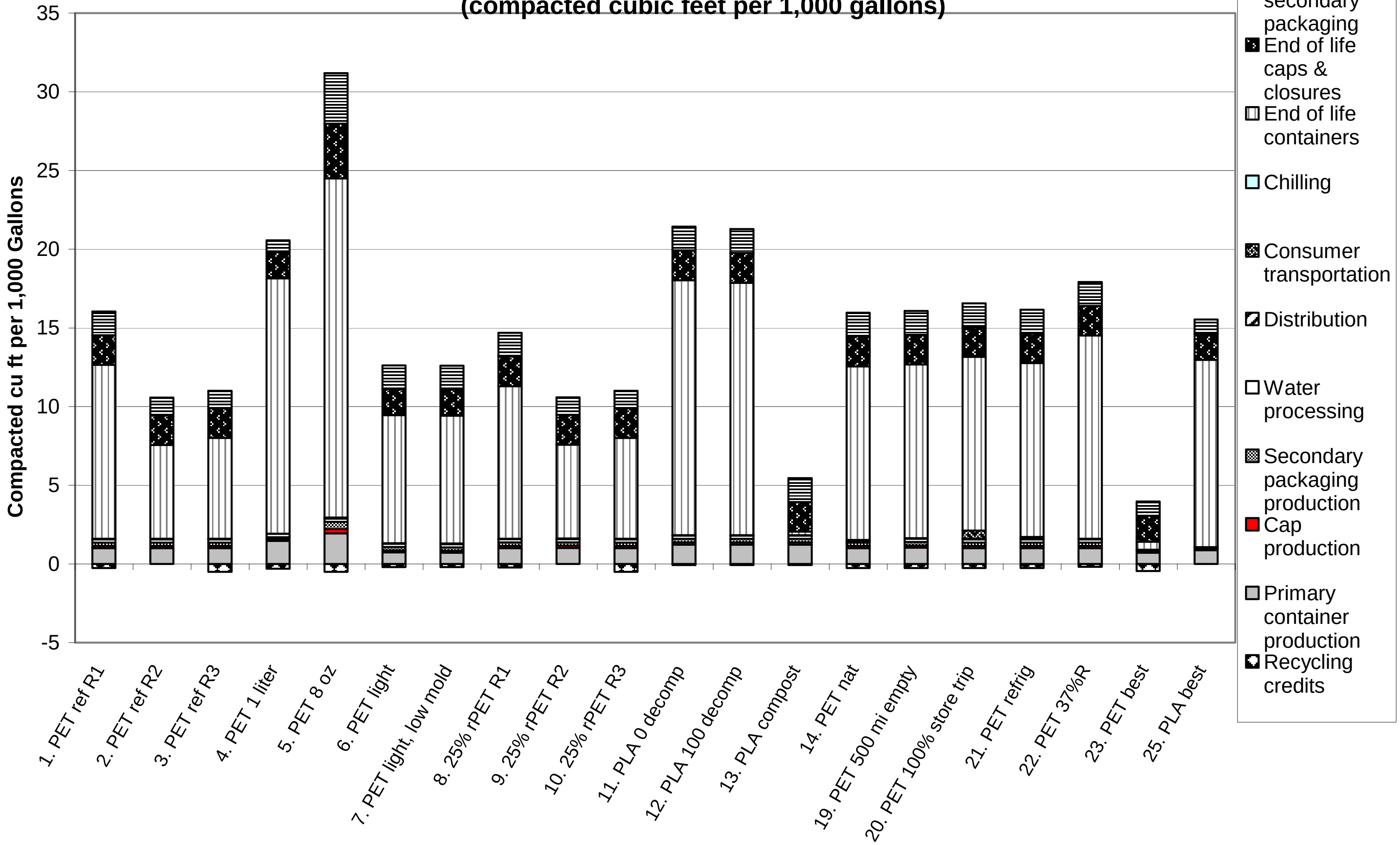
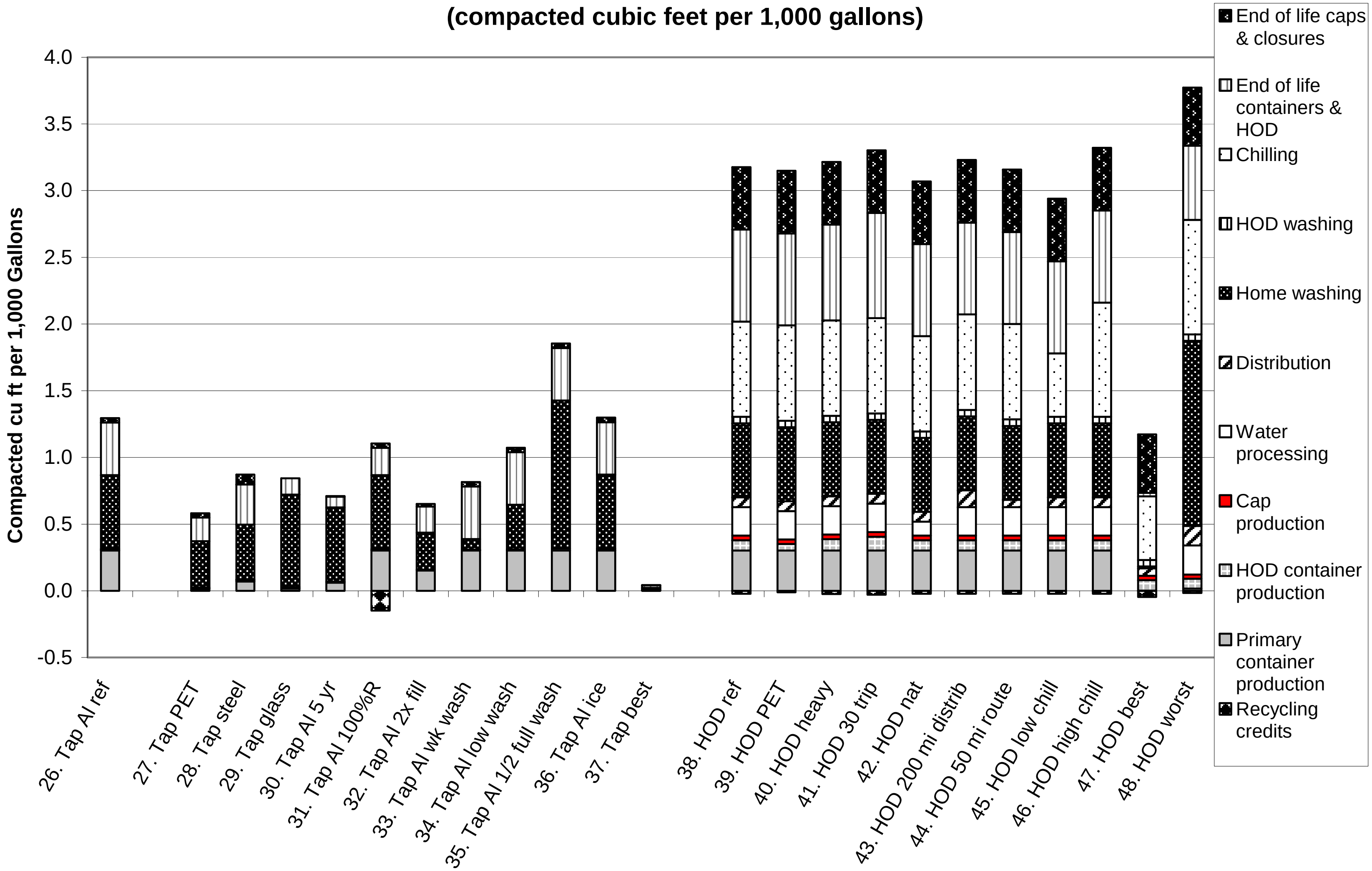


Figure 2-11. Solid Waste Volume Results for Tap and HOD Water Subscenarios (compacted cubic feet per 1,000 gallons)



CHAPTER 3

LIFE CYCLE IMPACT ASSESSMENT

INTRODUCTION

This chapter presents the results of the life cycle impact assessment (LCIA) phase of the drinking water systems LCA. Life cycle impact assessment is defined in ISO 14044 section 3.4 as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product." In the LCIA phase, the inventory of emissions from the LCI is first classified into categories in which the emissions may contribute to impacts on human health or the environment. Within each impact category, the emissions are then normalized to a common reporting basis, using characterization factors that express the impact of each substance relative to a reference substance.

The emissions used as the inputs to the impact assessment represent the aggregated emissions released over the life cycle of each drinking water system, not emissions *in* the drinking water. Assessment of variations in the quality of the drinking water (e.g., mineral content, variations in taste, temperature, etc.) delivered by the various systems was not included in this analysis.

The LCIA results are relative expressions of the *potential* of inventory flows to contribute to various health and environmental impacts and do not predict actual impacts on category endpoints (e.g., cancer cases, deaths, etc.), exceeding of thresholds, safety margins or risks. Various LCIA methodologies have been developed and can be used to conduct LCIA analyses. ISO 14044 does not require the use of any specific methodology or support underlying value-choices that may be used to group the impact categories.

The LCIA results in this chapter were derived from the LCI emissions (shown in the Chapter 2 Appendix tables) using the U.S. Environmental Protection Agency's impact assessment methodology known as TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts). In this chapter, results are presented and discussed for each impact category. No weighting schemes or value judgments are used to rank the relative importance of individual impact categories or arrive at a single impact "score."

LIFE CYCLE IMPACT ASSESSMENT METHODOLOGY

In the scoping phase of this study, the U.S. EPA's TRACI methodology was selected as the impact assessment methodology to be used, since it was developed to represent U.S. conditions (e.g., for fate and transport of chemical releases). TRACI tables for the classification of the emission inventory substances into impact categories, together with the characterization factors used to present impacts on a common basis within each category, are provided in Table 3-10 at the very end of this chapter. Each section of the table shows the emissions from the Chapter 2 inventory tables that are modeled as contributing to that impact category. A comparison of classification tables shows that some flows have the potential to contribute to multiple impact categories. Each flow was modeled as a potential contributor to impacts in all relevant impact categories. TRACI contains characterization factors for many more substances than are shown in the table at the end of this chapter; only the characterization factors for emissions from the Chapter 2 inventory are shown in the table.

For each impact category, the relevant emissions from the inventory tables are multiplied by their characterization factors to arrive at the impacts reported in the impact results tables. The TRACI table is provided for transparency and as a reference for the discussion of the impacts reported in the results tables.

TRACI Methodology and Impact Categories

The TRACI home page[27] provides the following summary description of the methodology:

> “To develop TRACI, impact categories were selected, available methodologies were reviewed, and categories were prioritized for further research. During the impact assessment methodology research phase, consistency with previous modeling assumptions (especially of the U.S. EPA) was important for every category. The human health cancer and non-cancer categories were heavily based on the assumptions made for the U.S. EPA Risk Assessment Guidance for Superfund and the U.S. EPA's Exposure Factors Handbook. For categories such as acidification and smog formation, detailed US empirical models, such as those developed by the US National Acid Precipitation Assessment Program and the California Air Resources Board, allowed the inclusion of the more sophisticated location specific approaches and location specific characterization factors. When there was no EPA precedent, assumptions and value choices were minimized by the use of midpoints.

> “Methodologies were developed specifically for the US using input parameters consistent with US locations for the following impact categories - acidification, smog formation, eutrophication, human cancer, human non-cancer, and human criteria effects. Probabilistic analyses allowed the determination of an appropriate level of sophistication and spatial resolution necessary for impact modeling for several categories, yet the tool was designed to accommodate current inconsistencies in practice (e.g., site specific information is often not available).

27 http://www.epa.gov/nrmrl/std/sab/traci/

"TRACI's modular design allows the compilation of the most sophisticated impact assessment methodologies that can be utilized in software developed for PCs. Where sophisticated and applicable methodologies didn't exist, research was conducted by the use of various simulations to determine the most appropriate characterization factors to represent the various conditions within the US…"

The following potential impacts are reported in this chapter, using TRACI characterization factors as published in SimaPro 7.1 software:

1. Acidification potential;
2. Carcinogenic potential;
3. Ecotoxicity potential;
4. Eutrophication potential;
5. Global Warming potential;
6. Non-carcinogenic potential;
7. Ozone depletion potential;
8. Respiratory Effects potential;
9. Smog potential.

Each impact category is described in more detail later in this chapter.

In reviewing the impact tables, the reader will note that the scenarios designated "best case" and "worst case" do not necessarily show the lowest (or highest) results in *all* subcategories. For example, for the tap and HOD scenarios, the results are dominated by home washing of reusable drinking containers. Thus, the "best case" overall is for the PET reusable drinking container, which has the largest capacity (fewer container washings per 1,000 gallons consumed), even though some impacts for producing the container may be higher than other containers. Similarly, the "worst case" overall is for the drinking glass, which has the smallest capacity and requires the most container washings per 1,000 gallons consumed, even though its container production impacts may be lower than other containers.

In addition, for some parameters it does not make sense to independently define certain parameters, since some are linked for practical purposes. An example would be the bottled water "worst case" of spring water trucked from the Eastern U.S. to Oregon. Although purified municipal water has higher processing burdens than natural water, it is assumed that purified municipal water would be sourced locally rather than transported across the country. Since the impacts for long-distance transportation are so much greater than the impacts for water processing, the "worst case" scenario uses spring water transported long distances rather than purified municipal water transported shorter distances.

Impact Assessment Limitations

The results for human health- and toxicity- related impacts, such as human cancer and non-cancer potentials and ecotoxicity, should be used with caution in light of some of the intrinsic limitations of life cycle impact assessments:

- Spatial and temporal resolution is lost in a life cycle assessment. When emissions from individual unit processes occurring in different locations over different time intervals are normalized to a functional unit of product output (in this case, 1,000 gallons of drinking water), the temporal and geographical characteristics needed to assess local health and environmental impacts are lost. The LCI results used as the starting point for the LCIA do not distinguish between emissions released instantaneously and locally and those released over a large geographical area over a long period of time.
- Similarly, LCI does not track the concentrations at which emissions are released into the natural environment or direct human contact. In contrast to threshold-driven environmental and toxicological mechanisms, LCA is based on a linear extrapolation of mass loadings with the assumption that this loading contributes to health or environmental effects. While the linear extrapolation of mass loadings is a reasonable approach for impact categories that are global or regional (such as global warming potential and acidification), it is not as appropriate a measure for human health- and toxicity- related impacts.

Readers should also recognize that LCIA methodologies cannot be considered to be wholly inclusive of all toxic chemicals. The TRACI list of chemicals with human toxicity potentials was developed using the Toxic Release Inventory (TRI) chemicals which had the highest production and emission volumes in the U.S. at the time of the research. When sufficient data was not available to conduct the calculations for fate and/or toxicity of certain chemicals, then these chemicals were not included. Future plans call for the expansion of TRACI to include a more comprehensive list of chemicals, especially in the categories of human health cancer and noncancer[28].

In addition to the intrinsic limitations and uncertainties of LCIA methodologies described above, which apply to all impact categories, it should be recognized that a number of critical issues regarding metals are imperfectly dealt with by present ecotoxicity characterization models, according to the Apeldoorn Declaration, the findings of a group of specialists in the areas of LCA (Life Cycle Assessment), LCIA (Life Cycle Impact Assessment) and Risk Assessment who convened in Apeldoorn, The Netherlands, in April 2004 to discuss the current practices and complications of LCIA methodologies for non-ferrous metals.[29] The purpose of the workshop was to provide input to the UNEP/SETAC Life Cycle Initiative on issues surrounding metal characterization by

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28 Communication with Jane Bare, U.S. EPA, TRACI developer, August 2006.

29 http://media.leidenuniv.nl/legacy/declaration_of_apeldoorn.pdf

currently available ecotoxicity-based LCIA methods. Concerns about waterborne metal ecotoxicity modeling include the need for improved data on speciation (which determines toxicity and bioavailability of the metal emissions), and persistence (taking into account the amount of time that the emissions are bioavailable before they are converted to other species and/or adsorbed to soils, sediments, and suspended matter). The LCIA Toxic Impacts Task Force of the UNEP/SETAC Life Cycle Initiative has formed a subgroup to address specific issues and guide the work towards establishment of sound characterization factors for non-ferrous metal emissions that may be released from chemical or physical processes or from the production and combustion of fuels.

Finally, some of the unit process emissions reported in the LCI are not identified in sufficient detail to enable inclusion in the impact assessment (e.g., releases reported by data sources as “metal compounds” or “unspecified acids”). Insufficiently speciated emissions are reported in the Chapter 2 emission inventory tables but are not assigned characterization factors in the LCIA.

As noted in the introduction to this chapter, this analysis does not apply value judgments to rank the importance of individual impacts, nor are subjective weighting schemes used to arrive at a single impact score. Results for each impact are presented and discussed individually in the following sections, presented in alphabetical order.

The descriptions quoted for each impact category in the sections below are excerpted from “TRACI – The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts” by Bare, J.C., G.A. Norris, D.W. Pennington, and T. McKone, published in 2003 in the *Journal of Industrial Ecology*.

Acidification Potential

“Acidification comprises processes that increase the acidity (hydrogen ion concentration, [H^+]) of water and soil systems. Acid rain generally reduces the alkalinity of lakes... Acid deposition also has deleterious (corrosive) effects on buildings, monuments, and historical artifacts. This category is used to indicate the potential of emissions to contribute to wet or dry acid deposition.”[30]

Table 3-1 presents acidification potential results for all drinking water scenarios by life cycle stage. In TRACI, results are expressed on a normalized basis of moles of hydrogen ion. Figure 3-1 shows results for all bottled water systems, and Figure 3-2 shows results excluding long-distance transport scenarios (in order to provide an expanded view of the relative contributions of other life cycle stages). Figure 3-3 shows results for tap and HOD systems.

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30 Bare, et al, 2003.

The LCIA results show that the majority of the acidification potential for bottled water systems is associated with the production of the bottles, caps, and secondary packaging. For the long-distance transport scenarios, acidification impacts for distribution are also significant. The majority of the acidification impacts are associated with the combustion of fossil fuels for process and transportation energy, which produces emissions of nitrogen oxides and sulfur oxides.

Fossil fuel-related emissions also dominate the acidification results for the tap and HOD systems. For tap scenarios, energy use for home washing of reusable containers accounts for the majority of the acidification potential. For the HOD scenarios, the steps with the largest contributions to acidification potential are those that use the most energy, namely home washing, chilling, and, to a lesser extent, transportation.

Carcinogenic Potential

For human cancer and noncancer effects, “The methodology developed for TRACI is based on a multimedia fate, multipathway human exposure and toxicological potency approach using CalTOX. Twenty-three exposure pathways were taken into account within the analysis, including inhalation, ingestion of water and various plants and animals, and dermal contact with the soil and water. Toxicity is based on cancer potencies for carcinogens and reference doses or concentrations for noncarcinogens. Human toxicity potentials (HTPs) were calculated for 330 chemicals, including chemicals representing 80% of the total weight of toxics release inventory releases in 1997. Probabilistic analysis of uncertainty using the proposed model indicates that uncertainty associated with half-life and toxicity represents a large portion of the total uncertainty in calculating HTPs.”[31]

Results for this impact category are normalized to the basis of equivalent pounds of benzene. Table 3-2 reports carcinogenic potential results for all drinking water scenarios by life cycle stage. Figure 3-4 shows results for all bottled water systems, and Figure 3-5 shows results excluding long-distance transport scenarios. Figure 3-6 shows results for tap and HOD systems.

The TRACI characterization factor table (at the end of this chapter) shows that dioxin emissions have by far the greatest impact factors compared to all other substances contributing to carcinogenic potential in this analysis. Trace emissions of dioxin are associated with the combustion of coal, residual and distillate oils, and wood. Thus, the use of these fuels as direct process fuels and fuels for electricity generation are the dominant factor in the carcinogenic potential results.

For bottled water systems, the largest share of carcinogenic potential is associated with the production of secondary packaging. This is from trace dioxin emissions associated with combustion of wood wastes for process fuel at paperboard mills. The high recycling rate for corrugated results in a substantial credit that helps offset the

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[31] Ibid.

corrugated production emissions. For the tap and HOD scenarios, the processes that are the largest users of electricity have the greatest carcinogenic potential, due to dioxin emissions from coal combustion for electricity generation. Because production of virgin aluminum is very electricity-intensive, the aluminum reusable container shows a higher carcinogenic potential than the other reusable containers, even with the use of hydropower for a large share of the smelting energy.

Ecotoxicity Potential

TRACI uses this category to report the potential of emissions to adversely affect the health of ecosystems. The normalization basis is pounds of 2,4-Dichlorophenoxyacetic acid (2,4-D), a widely used herbicide. Table 3-3 presents eoctoxicity potential results for all drinking water scenarios by life cycle stage. Figure 3-7 shows results for all bottled water systems, and Figure 3-8 shows results excluding long-distance transport scenarios. Figure 3-9 shows results for tap and HOD systems.

Ecotoxicity results for bottled water systems are generally dominated by bottle production (except for the long-distance transport scenarios, where distribution makes the largest contribution). Of the ecotoxicity potential for bottle production, over half is associated with process emissions, primarily waterborne process emissions of metals from crude oil and natural gas extraction. As noted in the Limitations section, there is a recognized need to improve LCIA modeling of ecotoxicity of metal emissions, particularly in the areas of speciation and persistence. Although the ecotoxicity results shown for PLA bottles are lower than for PET bottles,, it should be noted that the results for PLA bottles do not include the effect of emissions from production and application of agricultural chemicals such as fertilizers, pesticides, and herbicides used in corn growing. Agricultural chemicals have ecotoxicity and eutrophication effects, but the types and quantities of chemicals that are used vary, and the amount of applied chemicals that end up in runoff are highly dependent on local geography, rainfall, etc. Agricultural chemical emissions were not included in the modeling for this analysis.

The contributions of metal emissions from oil production also influence the ecotoxicity potential for scenarios that use more transport fuel, e.g., the long-distance transport scenarios and scenarios 20 and 24, which model a dedicated consumer vehicle trip to purchase bottled water.

For the tap and HOD systems, transportation and consumer washing dominate the ecotoxicity results. Transportation ecotoxicity is associated with metal emissions from the extraction of crude oil used to produce the petroleum-derived transportation fuels. Ecotoxicity results for washing are attributed to metal emissions from extraction of natural gas that is used for water heating and dioxin emissions associated with coal combustion to generate electricity for water heating and dishwasher operation.

Eutrophication Potential

"Eutrophication is the fertilization of surface waters by nutrients that were previously scarce. When a previously scarce (limiting) nutrient is added, it leads to the proliferation of aquatic photosynthetic plant life. This may lead to a chain of further consequences, including foul odor or taste, death or poisoning of fish or shellfish, reduced biodiversity, or production of chemical compounds toxic to humans, marine mammals, or livestock."[32]

Eutrophication potential impacts in TRACI are expressed on the basis of pounds of nitrogen equivalents. Table 3-4 reports eutrophication potential results for all drinking water scenarios by life cycle stage. Figures 3-10 and 3-11 show results for all bottled water systems, with and without long-distance transport scenarios, and Figure 3-12 shows results for tap and HOD systems.

For the bottled water scenarios, long-distance transport and PLA bottle production show the highest eutrophication potential. The transport eutrophication potential can be traced to emissions from fuel combustion, while the PLA eutrophication potential is due to emissions from production and use of nitrogen and phosphate fertilizers for growing the corn used as a feedstock to PLA production. Emissions from production of corrugated packaging (primarily BOD and COD emissions) also make a substantial contribution to eutrophication potential for the bottled water systems.

For the tap and HOD system subscenarios, the majority of eutrophication is fuel-related, so results are highest for the steps with the largest energy consumption: transportation, chilling, and washing. Eutrophication from HOD container production is also predominantly fuel-related.

Sensitivity Analysis on Dishwasher Detergent Contribution to Eutrophication. As noted in Appendix I, the decision was made to exclude detergent manufacture from the analysis based on past studies that indicated that the energy requirements for detergent manufacture are small in comparison to the energy requirements for the washing process. However, the use of detergents containing phosphates can contribute to eutrophication impacts.

Within the washing subscenarios evaluated for the tap and HOD systems, there can be large differences in results for washing of reusable containers in home dishwashers. Results can vary widely depending on the size of the container, the number of times the container is filled daily, how frequently the container is washed, and the volume utilization of the dishwasher. Within these scenarios there are also possibilities for variations in detergent use. Automatic dishwasher detergents commonly contain phosphate; however, non-phosphate automatic dishwasher detergents are also increasingly available. A bill was passed in Oregon in March 2009 prohibiting the sale of any cleaning agent containing more than 0.5 percent phosphorus by weight, effective July

32 Ibid.

1, 2010. In order to evaluate the potential contribution of the use of phosphate detergent with 0.5 percent phosphorus, a sensitivity analysis was run on the eutrophication results for tap and HOD systems.

The quantity of phosphorus per dishwasher load was estimated based on the weight of a Cascade Advanced Power 2 in 1 Action Pac®. A container of 90 individual gel-pacs weighed 1.62 kg, which equates to 0.040 lb of detergent per dishwasher load. Although current gel-pacs contain a maximum of 8 percent phosphorus by weight, a similar weight gel-pac with 0.5 percent phosphorus would contain 0.040 lb x 0.5% = 0.0002 lb of phosphorus.

Next, the ranges in dishwasher cycles per 1,000 gallons of drinking water were calculated. This was calculated as (1,000 gal drinking water x 128 fluid oz/gal) / (fluid oz/reusable container x daily fills x days use before washing) / 110 containers per dishwasher load.[33] For example, for a 20 ounce aluminum container filled once per day and washed daily, the total number of dishwasher cycles per 1,000 gal drinking water is (1,000 x 128) / (20 x 1 x 1) / 110 = 58.2 dishwasher loads. Multiplying by the weight of phosphorus in one detergent capsule per load gives a total phosphorus weight of 0.0002 lb phosphorus/load x 58.2 loads = 0.012 lb of phosphorus in the dishwashing effluent water per 1,000 gal of drinking water consumed.

This amount was adjusted to take into account the phosphorus removal efficiency in municipal wastewater treatment. A literature source indicated that the removal rate for phosphorus in a single-stage activated sludge treatment process is around 20 percent, while removal efficiency for a two-stage process is around 45 percent.[34] For single-stage treatment, this results in net phosphorus releases of 80% x 0.012 = 0.092 lb of phosphorus per 1,000 gal drinking water consumed. Multiplying by the TRACI eutrophication characterization factor of 7.29 lb N equivalent per lb of phosphorus, the eutrophication impact for use of 0.5% P detergent is 0.067 lb N equivalent per 1,000 gal drinking water consumed from 20 oz reusable containers washed after each filling.

As with other dishwashing impacts, multiple fills of the container before washing or multiple days use before washing greatly reduce the number of container washings (and thus detergent use) per 1,000 gal of drinking water consumed; however, using smaller containers or running the dishwasher when it is less than full increases the detergent use per 1,000 gallons. The following table summarizes ranges of phosphorus and eutrophication potential in dishwasher effluent for several additional scenarios.

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33 As documented in Appendix I, based on the volume of the dishwasher and the space occupied by one container, it was estimated that one dishwasher load could hold 110 containers. Thus, each container washing is allocated 1/110 of a dishwasher cycle.

34 **Estimation of Costs of Phosphorus Removal in Wastewater Treatment Facilities: Construction *De Novo.*** Water Policy Working Paper #2004-010. Jiang, F., M.B. Beck, R.G. Cummings, K. Rowles, and D. Russell. June 2004.

Ranges of Eutrophication for Use of Dishwashing Detergent with 0.5% Phosphorus

	Dishwasher cycles per 1,000 gallons consumed	P in effluent before treatment	P in effluent after treatment*		TRACI N eq/ lb P	N eq in effluent after treatment	
			20% removal	45% removal		20% removal	45% removal
100% use of phosphate detergent capsules with 0.00020 lb/P per capsule							
27 oz container filled twice daily, washed weekly	3.08	0.00061	0.00049	0.00034	7.29	**0.0036**	**0.0024**
20 oz container filled once daily, washed daily	58.2	0.012	0.0092	0.0063	7.29	**0.067**	**0.046**
16 oz container filled once daily, washed daily	72.7	0.014	0.012	0.0079	7.29	**0.084**	**0.058**
16 oz container filled once daily, washed daily, half-full dishwasher	145	0.029	0.023	0.016	7.29	**0.17**	**0.12**

* Using average removal rate of 20% for standard activated sludge treatment and 45% for two-stage activated sludge treatment.

As shown in Table 3-4, eutrophication potential for most bottled water system subscenarios (excluding long distance transport scenarios) falls within the range of 0.18 to 0.76 lb N eq, while results for tap and HOD systems excluding detergent use were much lower, at less than 0.05 lb N eq for most tap scenarios and 0.15 to 0.20 lb N eq for most HOD scenarios. Depending on the reusable container size and frequency of washing and efficiency of the wastewater treatment system in removing phosphorus from the dishwasher effluent, the use of phosphate detergent could add from 0.0024 to 0.17 lb N eq to the eutrophication potential for tap and HOD systems. Thus, use of phosphate detergent may significantly increase the eutrophication potential for reusable container systems to levels that are comparable with some Oregon bottled water scenarios.

Global Warming Potential

"The impact category of global climate change refers to the potential change in the earth's climate caused by the buildup of chemicals (i.e., "greenhouse gases") that trap heat from the reflected sunlight that would have otherwise passed out of the earth's atmosphere…TRACI uses global warming potentials, a midpoint metric proposed by the International Panel on Climate Change (IPCC), for the calculation of the potency of greenhouse gases relative to CO2 (IPCC 1996). The 100-year time horizons recommended by the IPCC and used by the United States for policy making and reporting (U.S. EPA 2001) are adopted within TRACI. The final sum, known as the global warming index, indicates the potential contribution to global warming."[35]

Table 3-5 presents GWP results for all drinking water scenarios by life cycle stage. Figures 3-13 and 3-14 show results for all bottled water systems, with and without long-distance transport scenarios. Figure 3-15 shows results for tap and HOD systems.

The GWP results in Table 3-5 the figures include emissions released directly from processes as well as emissions from the production and combustion of fuels used for process and transportation energy. For end-of-life management of containers and

35 Ibid.

packaging, the reported emissions include emissions from collection and transport of postconsumer materials, operation of landfill equipment, and emissions from combustion or decomposition of containers and packaging. As described in Chapter 1, emissions from decomposition of landfilled corrugated paperboard (used for packaging of bottled water) are based on maximum experimental decomposition. The end-of-life GWP results should be considered to have a higher uncertainty than the process and fuel-related GWP results. The majority of GWP for each system is associated with the production and combustion of fuels.

For the bottled water systems, GWP is dominated by fossil fuel emissions associated with production of bottles and transportation of filled containers. The PLA bottle scenarios (scenarios 11 through 13 and 25) show some interesting results. When PLA containers are modeled as being landfilled with 0% decomposition (scenarios 11 and 25) there is a large credit for the carbon content of the PLA that was removed from the atmosphere as carbon dioxide during growth of the corn plant and then sequestered in the landfill, for a net reduction in atmospheric carbon dioxide. When PLA containers are modeled as decomposing anaerobically in the landfill (scenario 12), there is a net increase in end-of-life GWP, associated with the percentage of generated methane that is released from the landfill without being captured and converted to carbon dioxide. When PLA containers are modeled as decomposing aerobically in a properly maintained industrial composting system (scenario 13), there is neither net sequestration or GWP increases from the PLA material, since the carbon content of the PLA is assumed to return to the atmosphere in the same form as it was removed during the corn’s growth cycle (as carbon dioxide).

On average, for the tap and HOD systems over 95 percent of GWP is fuel-related, so GWP is again highest for those processes that use the most energy. Although GWP from water treatment is small in comparison to other HOD life cycle stages, a comparison of scenario 42 (natural water with 90% ozone treatment and 50% UV treatment) and other subscenarios (with water treatment based on 100% ozone, UV, and reverse osmosis) shows that eliminating reverse osmosis substantially reduces the GWP for water processing (although the GWP from water processing is still small in comparison to other life cycle stages). In scenario 47 (UV treatment only), the water processing GWP is negligible compared to other life cycle stages.

Carbon Dioxide from Groundwater. As described in the drinking water treatment appendix, it has been documented that dissolved CO_2 in groundwater from unconfined aquifers can be one to two orders of magnitude higher than those found in surface water. Bottled springwater comes from underground aquifers, and 25 percent of Oregon households get their water from wells, although the largest water treatment utilities in Oregon (such as Portland, Eugene and Salem) all use surface water as their primary source.

Table 3-6 presents a summary of water use for drinking water processing, drinking container washing, and HOD container washing. For each water use category, the percentage of groundwater is shown, and the range of potential contribution of dissolved CO_2 in groundwater is shown.

For bottled drinking water systems, added CO_2 from groundwater ranges from 0 to 85 pounds of dissolved CO_2 per 1,000 gallons of drinking water delivered, with the highest results for natural spring water containing dissolved CO_2 at levels two orders of magnitude higher than surface water. For the tap water scenarios, the added CO_2 ranges from 2 to 56 pounds, with the highest contribution for containers that are washed in a high water use dishwasher that is run when it is half full. For the HOD water scenarios, added CO_2 ranges from 2 to 102 pounds of added CO_2. The highest added CO_2 is for the scenario with HOD spring water consumed from a drinking container that is washed after each use in a high water use dishwasher.

Because potential emissions from dissolved CO_2 in groundwater are more uncertain than other CO_2 emissions data, they are not included in Figures 3-13 through 3-15.

Non-carcinogenic Potential

This category is based on the potential of emissions to contribute to human health impacts other than cancer. Results are expressed in units of pounds of toluene equivalents.

Table 3-7 presents results for all drinking water scenarios by life cycle stage. Figures 3-16 and 3-17 show results for all bottled water systems, with and without long-distance transport scenarios, and Figure 3-18 shows results for tap and HOD systems.

The non-carcinogenic characterization factor for dioxin emissions is orders of magnitudes greater than the characterization factors for all other emissions contributing to this category; therefore the results are driven by systems' use of wood, coal, and residual and distillate oil as process fuels and fuels for the production of electricity. As a result, non-carcinogenic potential for the bottled water systems are dominated by secondary packaging production, due to the use of wood as process fuel in paperboard production. Corrugated recycling provides a significant offsetting credit for these emissions.

For the tap and HOD systems, which do not use corrugated packaging, the results are driven by dioxin emissions from the processes with the highest use of electricity (virgin aluminum production, container washing, and chilling).

Ozone Depletion Potential

"Stratospheric ozone depletion is the reduction of the protective ozone within the stratosphere caused by emissions of ozone-depleting substances. Recent anthropogenic emissions of chlorofluorocarbons (CFCs), halons, and other ozone-depleting substances are believed to be causing an acceleration of destructive chemical reactions, resulting in lower ozone levels and ozone "holes" in certain locations. These reductions in the level of ozone in the stratosphere lead to increasing ultraviolet-B (UVB) radiation reaching the earth… increasing UVB radiation can cause additional cases of skin cancer and cataracts. UVB radiation can also have deleterious effects on crops, materials, and marine life."[36]

TRACI expresses ozone depletion potential in units of CFC-11 (trichlorofluoremethane) equivalents. Table 3-8 presents ozone depletion potential (ODP) results for all drinking water scenarios by life cycle stage. Figures 3-19 and 3-20 show results for all bottled water systems, with and without long-distance transport scenarios. Figure 3-21 shows results for tap and HOD systems.

For the PET bottled water scenarios, the majority of ODP is associated with secondary packaging: process emissions of HCFC-22 associated with production of LDPE film case wrap, and fuel-related emissions of carbon tetrachloride (tetrachloromethane) from combustion of wood waste in the production of paperboard packaging. Corrugated recycling provides some offset for these emissions, but no recycling was modeled for LDPE film case wrap, since few curbside recycling programs accept plastic film. Consumers who have access to film dropoff locations (e.g., at grocery and drug stores) often do not utilize these dropoffs or use them only for dropping off postconsumer plastic bags and not other types of plastic film.

As with most other potential impacts for tap and HOD water scenarios, ODP is dominated by fuel-related emissions associated with energy use for washing of reusable containers in a home dishwasher, HOD chilling, and production of virgin aluminum reusable drinking containers. However, for the HOD scenarios, process emissions from LDPE cap production also make a substantial contribution to total ODP.

Respiratory Effects Potential

TRACI expresses respiratory effects potential in units of equivalent pounds of PM 2.5 (particulate matter smaller than 2.5 microns in size). Particulate matter (PM) is a complex mixture of tiny particles and liquid droplets that may include acids, organics, metals, and soil or dust. Particles smaller than 10 microns in diameter are of most concern to EPA because of the health effects they can cause when they enter the lungs. The LCI emissions inventory includes emissions of PM 10, PM 2.5, and PM (unspecified). In this analysis, unspecified PM is modeled as PM 10. This is a moderate approach, as the impact factor for PM 10 (0.60) is lower than the factor for PM 2.5 (1.0), but higher than the factor of 0.33 for TSP (total suspended particulates).

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36 Ibid.

Table 3-9 presents respiratory effects potential results for all drinking water scenarios by life cycle stage. Figures 3-22 and 3-23 show results for all bottled water systems, with and without long-distance transport scenarios. Figure 3-24 shows results for tap and HOD systems.

The largest share of potential respiratory impacts for the bottled water systems are associated with container production. These are predominantly emissions associated with the combustion of fuels for process energy. The majority of potential respiratory impacts for the tap and HOD systems are also fuel-related, so the most energy-intensive processes (container washing and HOD chilling) have the highest respiratory impact results.

Smog Potential

While ozone high in the stratosphere protects the earth from UV radiation, ground-level ozone, commonly known as smog, can have adverse impacts on human health and ecosystems. Tropospheric ozone is formed when pollutants emitted by cars, power plants, chemical plants, and other sources react chemically in the presence of sunlight. Potential smog impacts are reported in units of equivalent pounds of nitrogen oxides.

Smog potential results for all drinking water scenarios by life cycle stage are shown in Table 3-10. Figures 3-25 and 3-26 show results for all bottled water systems, with and without long-distance transport scenarios. Figure 3-27 presents results for tap and HOD systems.

For the bottled water systems, the subscenarios with the largest smog potential are the long-distance transport scenarios (scenarios 15-18 and scenario 24). Excluding these scenarios, the largest contributions to smog potential are from bottle production. For PET bottle production, the smog potential is fairly evenly divided between process and fuel-related emissions, while for PLA bottles the majority of the smog potential is fuel-related. The majority of the smog potential for glass bottles is from process emissions of nitrogen oxides from the glass manufacturing process. Recycling of PET and glass containers provides some offset credit for the container material production emissions contributing to the smog potential.

For tap and HOD systems, over 95 percent of total smog potential is fuel-related, so the life cycle stages with the highest energy use again dominate results.

Table 3-1. Acidification Potential by Life Cycle Stage for Drinking Water System Scenarios (page 1 of 2)
(H+ mole equivalents per 1,000 gallons)

	Bottled Water												
	PET ref R1	PET ref R2	PET ref R3	PET 1 liter	PET 8 oz	PET light	PET light, low mold	25% rPET R1	25% rPET R2	25% rPET R3	PLA 0 decomp	PLA 100 decomp	PLA compost
Bottled Water Scenarios	1	2	3	4	5	6	7	8	9	10	11	12	13
Production													
Disposable bottle	372	372	372	547	727	274	269	342	311	372	355	355	355
Caps and closures	62.3	62.3	62.3	54.5	115	54.5	54.5	62.3	62.3	62.3	62.3	62.3	62.3
Secondary packaging	64.1	64.1	64.1	32.0	135	64.1	64.1	64.1	64.1	64.1	64.1	64.1	64.1
Processes													
Water processing	39.3	39.3	39.3	39.3	39.3	39.3	39.3	39.3	39.3	39.3	39.3	39.3	39.3
Filling	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52
Distribution	16.9	16.9	16.9	17.0	17.5	16.8	16.8	16.9	16.9	16.9	16.9	16.9	16.9
Consumer transport	10.3	10.3	10.3	5.18	21.7	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3
Wastewater treatment	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Chilling	0	0	0	0	0	0	0	0	0	0	0	0	0
End of life management													
Containers	42.1	-0.12	84.5	61.8	82.2	31.0	31.0	42.1	-0.12	84.5	0.46	-29.7	-0.0071
Caps and closures	-0.37	-0.37	-0.37	-0.33	-0.69	-0.33	-0.33	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37
Secondary packaging	-1.28	-0.91	-0.58	-0.64	-2.70	-1.28	-1.28	-1.28	-0.91	-0.58	-1.28	-1.28	-1.28
Credits for recycling	-85.2	0	-168	-113	-168	-66.2	-66.2	-76.1	0	-168	-13.0	-13.0	-13.0
TOTAL	**522**	**565**	**482**	**645**	**968**	**424**	**419**	**500**	**504**	**482**	**535**	**505**	**535**

	Bottled Water											
	PET nat	PET Maine nat	PET Fiji nat	PET Fiji free sea	Glass France	PET 500 mi empty	PET 100% store trip	PET refrig	PET 37%R	PET best	PET worst	PLA best
Bottled Water Scenarios	14	15	16	17	18	19	20	21	22	23	24	25
Production												
Disposable bottle	372	398	823	823	2,133	410	372	372	372	269	816	256
Caps and closures	62.3	62.3	101	101	734	62.3	62.3	62.3	62.3	54.5	115	54.5
Secondary packaging	64.1	64.1	64.1	64.1	89.5	64.1	64.1	64.1	64.1	30.9	148	30.9
Processes												
Water processing	18.8	26.0	0.039	0.039	16.2	39.3	39.3	39.3	39.3	0.028	28.9	0.028
Filling	1.52	2.10	2.10	2.10	1.31	1.52	1.52	1.52	1.52	1.52	2.10	1.52
Distribution	43.9	1,104	2,601	321	4,054	16.9	16.9	16.9	16.9	6.68	1,144	6.69
Consumer transport	10.3	10.3	10.3	10.3	14.4	10.3	255	10.3	10.3	0.069	540	0.069
Wastewater treatment	0	0	0	0	0	0.13	0.13	0.13	0.13	0	0.0052	0
Chilling	0	0	0	0	0	0	0	21.9	0	0	92.6	0
End of life management												
Containers	42.1	42.1	87.0	87.0	89.7	42.1	42.1	42.1	25.0	101	-0.64	0.34
Caps and closures	-0.37	-0.37	-0.60	-0.60	-4.38	-0.37	-0.37	-0.37	-0.37	-0.33	-0.69	-0.33
Secondary packaging	-1.28	-1.28	-1.28	-1.28	-1.78	-1.28	-1.28	-1.28	-1.28	-0.59	-2.95	-0.59
Credits for recycling	-85.2	-85.2	-162	-162	-864	-85.2	-85.2	-85.2	-56.1	-169	-30.0	0
TOTAL	**528**	**1,622**	**3,525**	**1,244**	**6,263**	**560**	**767**	**544**	**534**	**294**	**2,852**	**350**

Table 3-1. Acidification Potential by Life Cycle Stage for Drinking Water System Scenarios (page 2 of 2)
(H+ mole equivalents per 1,000 gallons)

	Tap											
Tap Water Scenarios	Tap Al ref 26	Tap PET 27	Tap steel 28	Tap glass 29	Tap Al 5 yr 30	Tap Al 100%R 31	Tap Al 2x fill 32	Tap Al wk wash 33	Tap Al low wash 34	Tap Al 1/2 full wash 35	Tap Al ice 36	Tap best 37
Production												
Reusable drinking container	24.9	5.02	10.1	4.80	4.98	24.9	12.4	24.9	24.9	24.9	24.9	0.50
Caps and closures	1.13	1.01	2.46	0	0.23	1.13	0.56	1.13	1.13	1.13	1.13	0.10
Processes												
Water processing	1.87	1.55	1.65	2.08	1.87	1.87	1.45	1.15	1.27	2.70	2.38	1.04
Home washing of reusable container	122	76.2	90.4	152	122	122	61.0	17.4	68.3	244	122	3.05
Wastewater treatment	0.43	0.27	0.32	0.53	0.43	0.43	0.21	0.061	0.12	0.85	0.43	0.0055
Chilling	0	0	0	0	0	0	0	0	0	0	0	0
End of life management												
Containers	0.051	-0.0037	0.071	0.051	0.010	0.98	0.026	0.051	0.051	0.051	0.051	-3.7E-04
Caps and closures	-0.0067	-0.0060	-0.015	0	-0.0013	-0.0067	-0.0034	-0.0067	-0.0067	-0.0067	-0.0067	-6.0E-04
Credits for recycling	0	0	0	0	0	-11.6	0	0	0	0	0	0
TOTAL	**150**	**84.1**	**105**	**160**	**130**	**140**	**75.7**	**44.7**	**95.7**	**274**	**151**	**4.70**

	HOD										
HOD Water Scenarios	HOD ref 38	HOD PET 39	HOD heavy 40	HOD 30 trip 41	HOD nat 42	HOD 200 mi distrib 43	HOD 50 mi route 44	HOD low chill 45	HOD high chill 46	HOD best 47	HOD worst 48
Production											
Reusable drinking container	24.9	24.9	24.9	24.9	24.9	24.9	24.9	24.9	24.9	0.50	4.80
HOD bottle	25.2	16.5	27.8	33.7	25.2	25.2	25.2	25.2	25.2	25.2	24.2
Caps and closures	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	11.6	11.5
Processes											
Water processing	40.2	40.2	40.2	40.2	19.7	40.2	40.2	40.2	40.2	0.10	41.5
Filling	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52
Distribution	65.6	65.6	65.8	65.6	65.6	116	49.4	65.6	65.6	49.4	133
Home washing of reusable container	122	122	122	122	122	122	122	122	122	3.05	305
Industrial HOD washing	9.36	9.36	9.36	9.36	9.36	9.36	9.36	9.36	9.36	9.36	9.36
Wastewater treatment	0.59	0.59	0.59	0.59	0.46	0.59	0.59	0.59	0.59	0.040	1.23
Chilling	135	135	135	135	135	135	135	89.8	162	89.8	162
End of life management											
Containers	0.89	0.93	0.97	1.17	0.89	0.89	0.89	0.89	0.89	1.77	1.34
Caps and closures	-0.093	-0.093	-0.093	-0.093	-0.093	-0.093	-0.093	-0.093	-0.093	-0.086	-0.086
Credits for recycling	-9.42	-5.57	-10.4	-12.6	-9.42	-9.42	-9.42	-9.42	-9.42	-18.8	-8.17
TOTAL	**428**	**423**	**430**	**434**	**407**	**479**	**412**	**383**	**455**	**173**	**687**

Franklin Associates, A Division of ERG

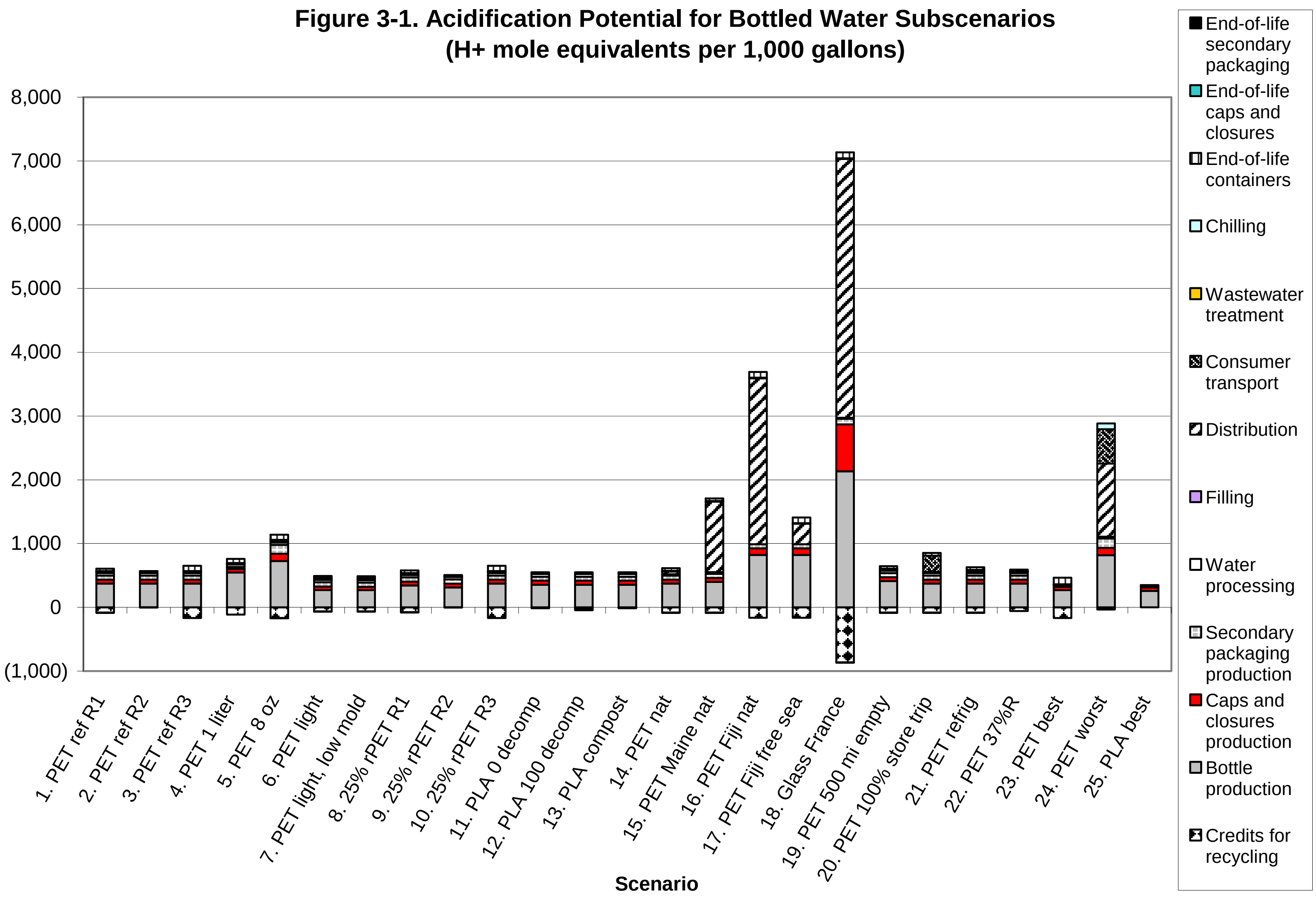
Figure 3-1. Acidification Potential for Bottled Water Subscenarios
(H+ mole equivalents per 1,000 gallons)
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
(1,000)
1. PET ref R1
2. PET ref R2
3. PET ref R3
4. PET 1 liter
5. PET 8 oz
6. PET light
7. PET light, low mold
8. 25% rPET R1
9. 25% rPET R2
10. 25% rPET R3
11. PLA 0 decomp
12. PLA 100 decomp
13. PLA compost
14. PET nat
15. PET Maine nat
16. PET Fiji nat
17. PET Fiji free sea
18. Glass France
19. PET 500 mi empty
20. PET 100% store trip
21. PET refrig
22. PET 37%R
23. PET best
24. PET worst
25. PLA best
Scenario
End-of-life secondary packaging
End-of-life caps and closures
End-of-life containers
Chilling
Wastewater treatment
Consumer transport
Distribution
Filling
Water processing
Secondary packaging production
Caps and closures production
Bottle production
Credits for recycling

Figure 3-2. Acidification Potential for Bottled Water Subscenarios excluding long-distance transport scenarios (H+ mole equivalents per 1,000 gallons)

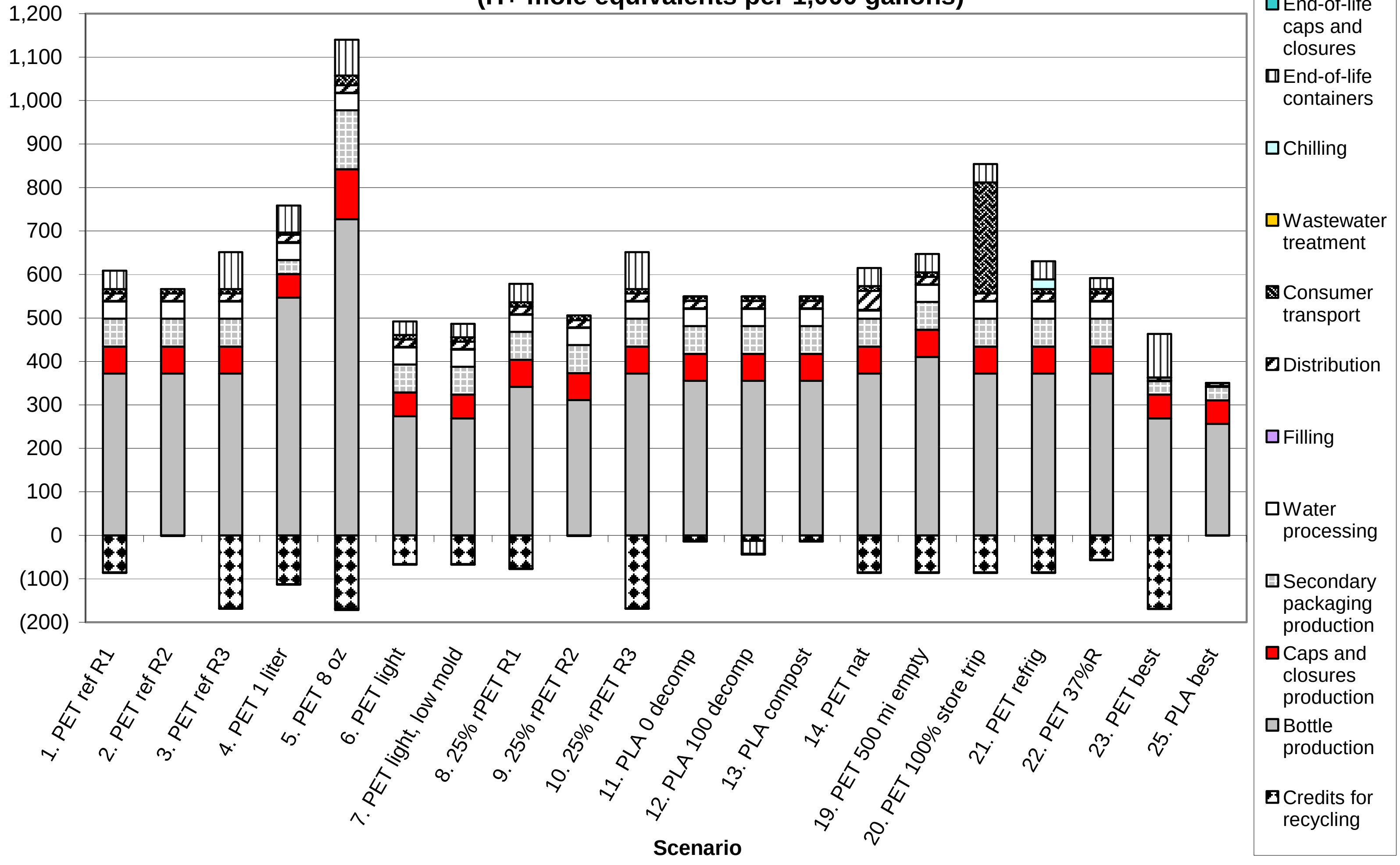

Figure 3-3. Acidification Potential for Tap and HOD Water Subscenarios (H+ mole equivalents per 1,000 gallons)

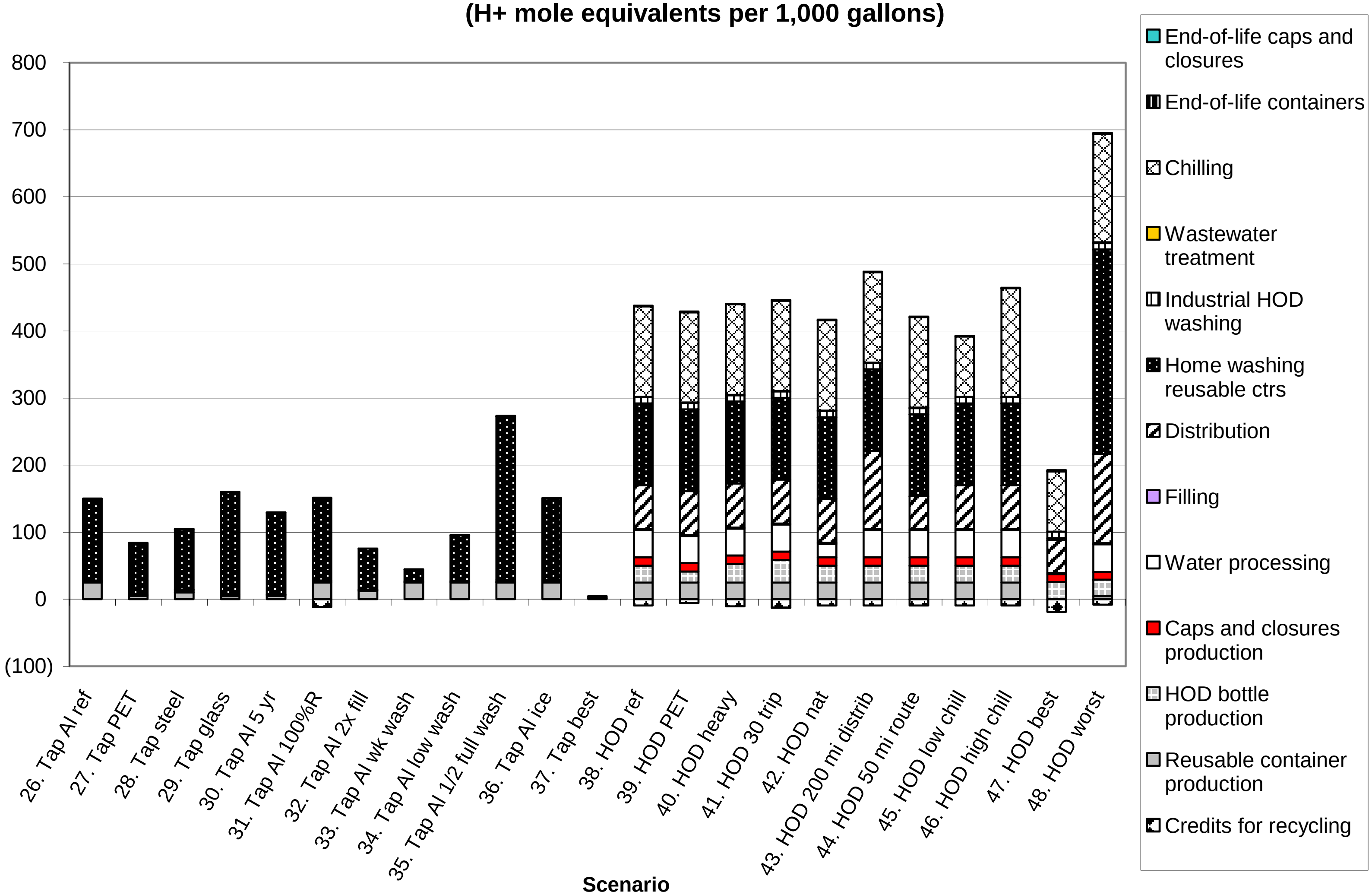

Table 3-2. Carcinogenic Potential by Life Cycle Stage for Drinking Water System Scenarios (page 1 of 2)
(lb benzene equivalents per 1,000 gallons)

	Bottled Water												
	PET ref R1	PET ref R2	PET ref R3	PET 1 liter	PET 8 oz	PET light	PET light, low mold	25% rPET R1	25% rPET R2	25% rPET R3	PLA 0 decomp	PLA 100 decomp	PLA compost
Bottled Water Scenarios	1	2	3	4	5	6	7	8	9	10	11	12	13
Production													
Disposable bottle	16.2	16.2	16.2	23.9	31.7	12.0	11.3	15.8	15.4	16.2	22.4	22.4	22.4
Caps and closures	2.29	2.29	2.29	2.00	4.23	2.00	2.00	2.29	2.29	2.29	2.29	2.29	2.29
Secondary packaging	68.1	68.1	68.1	34.1	144	68.1	68.1	68.1	68.1	68.1	68.1	68.1	68.1
Processes													
Water processing	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83	4.83
Filling	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Distribution	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Consumer transport	0.23	0.23	0.23	0.12	0.49	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Wastewater treatment	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014
Chilling	0	0	0	0	0	0	0	0	0	0	0	0	0
End of life management													
Containers	1.11	-0.17	2.65	1.63	2.16	0.82	0.82	1.14	-0.17	2.65	-0.35	-4.06	-0.37
Caps and closures	-0.094	-0.094	-0.094	-0.082	-0.17	-0.082	-0.082	-0.094	-0.094	-0.094	-0.094	-0.094	-0.094
Secondary packaging	-0.22	-0.15	-0.14	-0.11	-0.47	-0.22	-0.22	-0.22	-0.15	-0.14	-0.22	-0.22	-0.22
Credits for recycling	-26.1	0	-52.1	-13.4	-55.0	-26.0	-26.0	-26.0	0	-52.1	-25.7	-25.7	-25.7
TOTAL	**66.8**	**91.7**	**42.4**	**53.3**	**132**	**62.1**	**61.4**	**66.5**	**90.8**	**42.4**	**71.9**	**68.2**	**71.9**

	Bottled Water											
	PET nat	PET Maine nat	PET Fiji nat	PET Fiji free sea	Glass France	PET 500 mi empty	PET 100% store trip	PET refrig	PET 37%R	PET best	PET worst	PLA best
Bottled Water Scenarios	14	15	16	17	18	19	20	21	22	23	24	25
Production												
Disposable bottle	16.2	16.4	33.9	33.9	53.1	16.7	16.2	16.2	16.2	11.3	32.4	15.9
Caps and closures	2.29	2.29	3.72	3.72	27.0	2.29	2.29	2.29	2.29	2.00	4.23	2.00
Secondary packaging	68.1	68.1	68.1	68.1	95.1	68.1	68.1	68.1	68.1	0.74	157	0.74
Processes												
Water processing	2.31	2.35	0.0035	0.0035	3.16	4.83	4.83	4.83	4.83	0.0035	2.61	0.0035
Filling	0.19	0.19	0.19	0.19	0.25	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Distribution	0.49	12.3	7.15	3.57	26.7	0.19	0.19	0.19	0.19	0.074	12.7	0.075
Consumer transport	0.23	0.23	0.23	0.23	0.33	0.23	5.83	0.23	0.23	0.0016	12.3	0.0016
Wastewater treatment	0	0	0	0	0	0.014	0.014	0.014	0.014	0	5.7E-04	0
Chilling	0	0	0	0	0	0	0	2.70	0	0	11.4	0
End of life management												
Containers	1.11	1.11	2.29	2.29	5.07	1.11	1.11	1.11	0.48	3.35	-0.86	-0.26
Caps and closures	-0.094	-0.094	-0.15	-0.15	-1.10	-0.094	-0.094	-0.094	-0.094	-0.082	-0.17	-0.082
Secondary packaging	-0.22	-0.22	-0.22	-0.22	-0.31	-0.22	-0.22	-0.22	-0.22	-0.10	-0.51	-0.10
Credits for recycling	-26.1	-26.1	-26.4	-26.4	-50.9	-26.1	-26.1	-26.1	-25.9	-0.82	-59.4	0
TOTAL	**64.6**	**76.6**	**88.7**	**85.2**	**158**	**67.2**	**72.4**	**69.5**	**66.3**	**16.7**	**172**	**18.5**

Table 3-2. Carcinogenic Potential by Life Cycle Stage for Drinking Water System Scenarios (page 2 of 2)
(lb benzene equivalents per 1,000 gallons)

	Tap											
Tap Water Scenarios	Tap Al ref 26	Tap PET 27	Tap steel 28	Tap glass 29	Tap Al 5 yr 30	Tap Al 100%R 31	Tap Al 2x fill 32	Tap Al wk wash 33	Tap Al low wash 34	Tap Al 1/2 full wash 35	Tap Al ice 36	Tap best 37
Production												
Reusable drinking container	8.18	0.23	0.050	0.085	1.64	8.18	4.09	8.18	8.18	8.18	8.18	0.023
Caps and closures	0.041	0.037	0.090	0	0.0083	0.041	0.021	0.041	0.041	0.041	0.041	0.0037
Processes												
Water processing	0.22	0.18	0.20	0.25	0.22	0.22	0.17	0.14	0.15	0.32	0.28	0.12
Home washing of reusable container	12.7	7.96	9.44	15.9	12.7	12.7	6.37	1.82	7.75	25.5	12.7	0.35
Wastewater treatment	0.047	0.029	0.034	0.058	0.047	0.047	0.023	0.0066	0.013	0.093	0.047	6.0E-04
Chilling	0	0	0	0	0	0	0	0	0	0	0	0
End of life management												
Containers	7.4E-04	-0.0050	9.4E-04	6.1E-04	1.5E-04	0.044	3.7E-04	7.4E-04	7.4E-04	7.4E-04	7.4E-04	-5.0E-04
Caps and closures	-0.0017	-0.0015	-0.0037	0	-3.4E-04	-0.0017	-8.5E-04	-0.0017	-0.0017	-0.0017	-0.0017	-1.5E-04
Credits for recycling	0	0	0	0	0	-0.99	0	0	0	0	0	0
TOTAL	**21.2**	**8.43**	**9.80**	**16.3**	**14.6**	**20.3**	**10.7**	**10.2**	**16.1**	**34.1**	**21.3**	**0.50**

	HOD										
HOD Water Scenarios	HOD ref 38	HOD PET 39	HOD heavy 40	HOD 30 trip 41	HOD nat 42	HOD 200 mi distrib 43	HOD 50 mi route 44	HOD low chill 45	HOD high chill 46	HOD best 47	HOD worst 48
Production											
Reusable drinking container	8.18	8.18	8.18	8.18	8.18	8.18	8.18	8.18	8.18	0.023	0.085
HOD bottle	0.96	0.75	1.06	1.28	0.96	0.96	0.96	0.96	0.96	0.96	1.09
Caps and closures	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.52	0.52
Processes											
Water processing	4.93	4.93	4.93	4.93	2.42	4.93	4.93	4.93	4.93	0.012	5.08
Filling	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Distribution	0.80	0.80	0.80	0.80	0.80	1.36	0.59	0.80	0.80	0.59	1.57
Home washing of reusable container	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	0.35	31.8
Industrial HOD washing	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09
Wastewater treatment	0.065	0.065	0.065	0.065	0.050	0.065	0.065	0.065	0.065	0.0044	0.13
Chilling	16.6	16.6	16.6	16.6	16.6	16.6	16.6	11.0	19.9	11.0	19.9
End of life management											
Containers	0.067	0.073	0.074	0.090	0.067	0.067	0.067	0.067	0.067	0.16	0.11
Caps and closures	-0.023	-0.023	-0.023	-0.023	-0.023	-0.023	-0.023	-0.023	-0.023	-0.022	-0.022
Credits for recycling	-0.20	-0.15	-0.22	-0.27	-0.20	-0.20	-0.20	-0.20	-0.20	-0.40	-0.21
TOTAL	**45.9**	**45.8**	**46.0**	**46.2**	**43.4**	**46.5**	**45.7**	**40.4**	**49.2**	**14.5**	**61.4**

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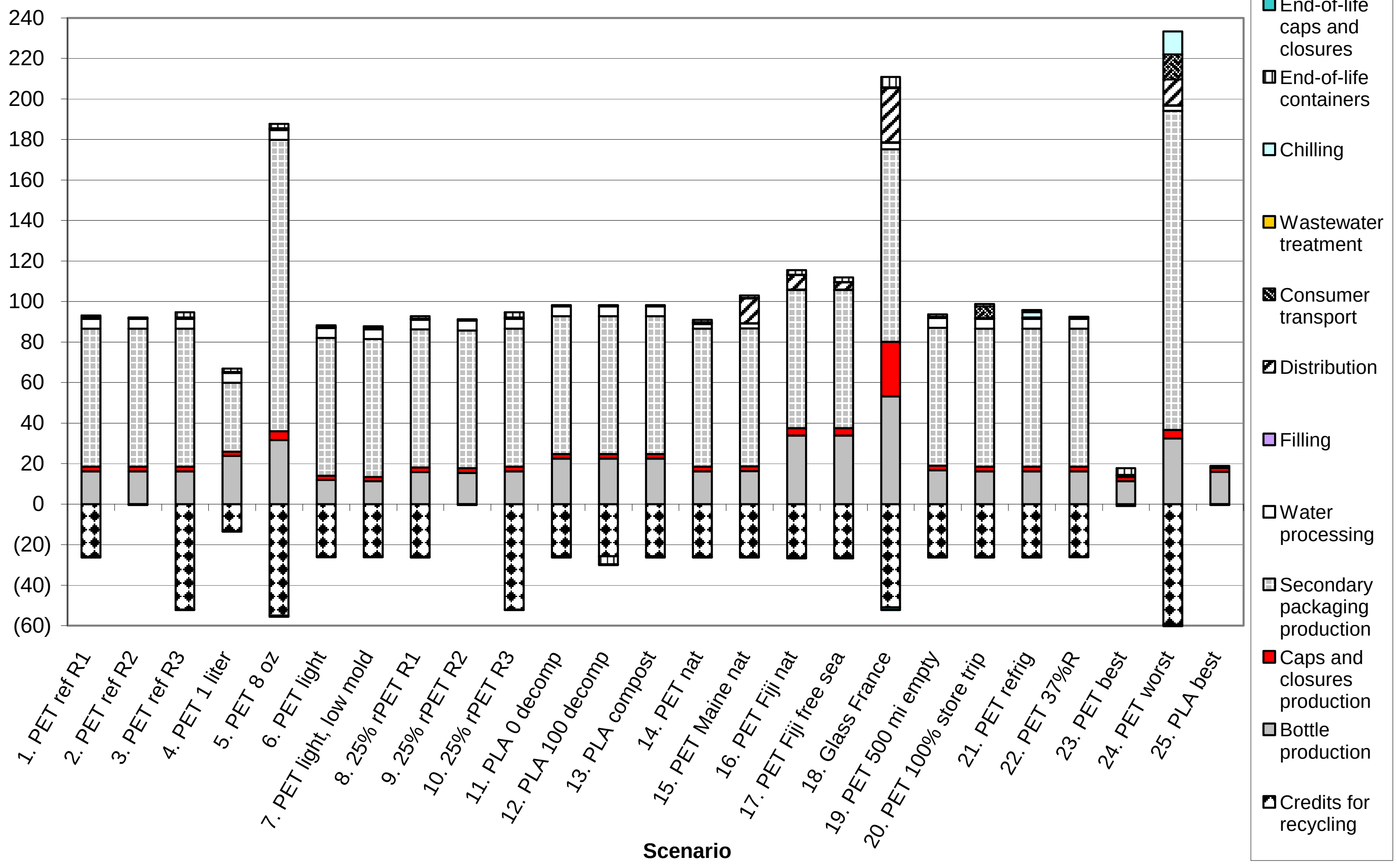
Figure 3-4. Carcinogenic Potential for Bottled Water Subscenarios (lb benzene equivalents per 1,000 gallons)



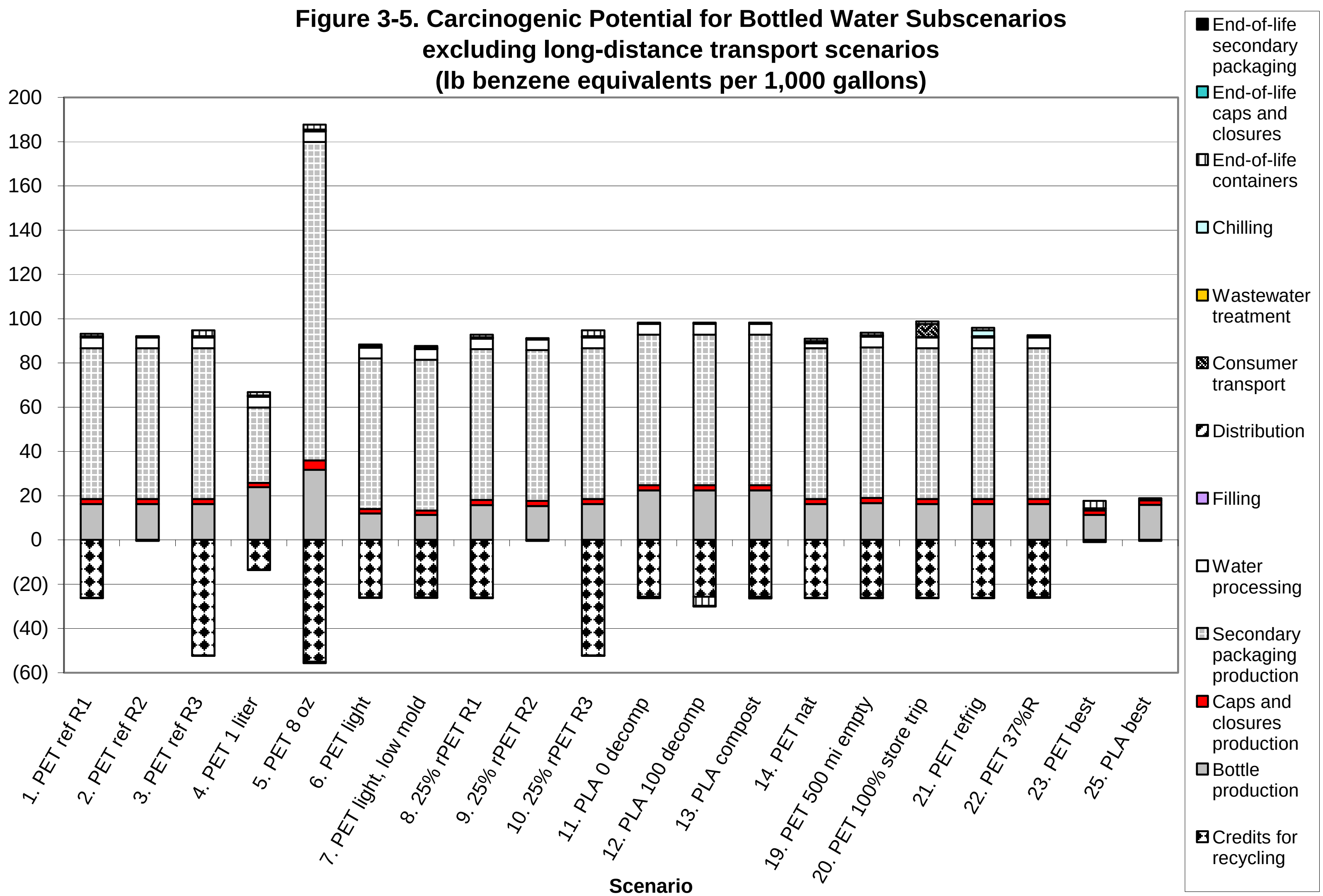


Figure 3-5. Carcinogenic Potential for Bottled Water Subscenarios
excluding long-distance transport scenarios
(lb benzene equivalents per 1,000 gallons)
200
180
160
140
120
100
80
60
40
20
0
(20)
(40)
(60)
1. PET ref R1
2. PET ref R2
3. PET ref R3
4. PET 1 liter
5. PET 8 oz
6. PET light
7. PET light, low mold
8. 25% rPET R1
9. 25% rPET R2
10. 25% rPET R3
11. PLA 0 decomp
12. PLA 100 decomp
13. PLA compost
14. PET nat
19. PET 500 mi empty
20. PET 100% store trip
21. PET refrig
22. PET 37%R
23. PET best
25. PLA best
Scenario
End-of-life secondary packaging
End-of-life caps and closures
End-of-life containers
Chilling
Wastewater treatment
Consumer transport
Distribution
Filling
Water processing
Secondary packaging production
Caps and closures production
Bottle production
Credits for recycling

Figure 3-6. Carcinogenic Potential for Tap and HOD Water Subscenarios (lb benzene equivalents per 1,000 gallons)

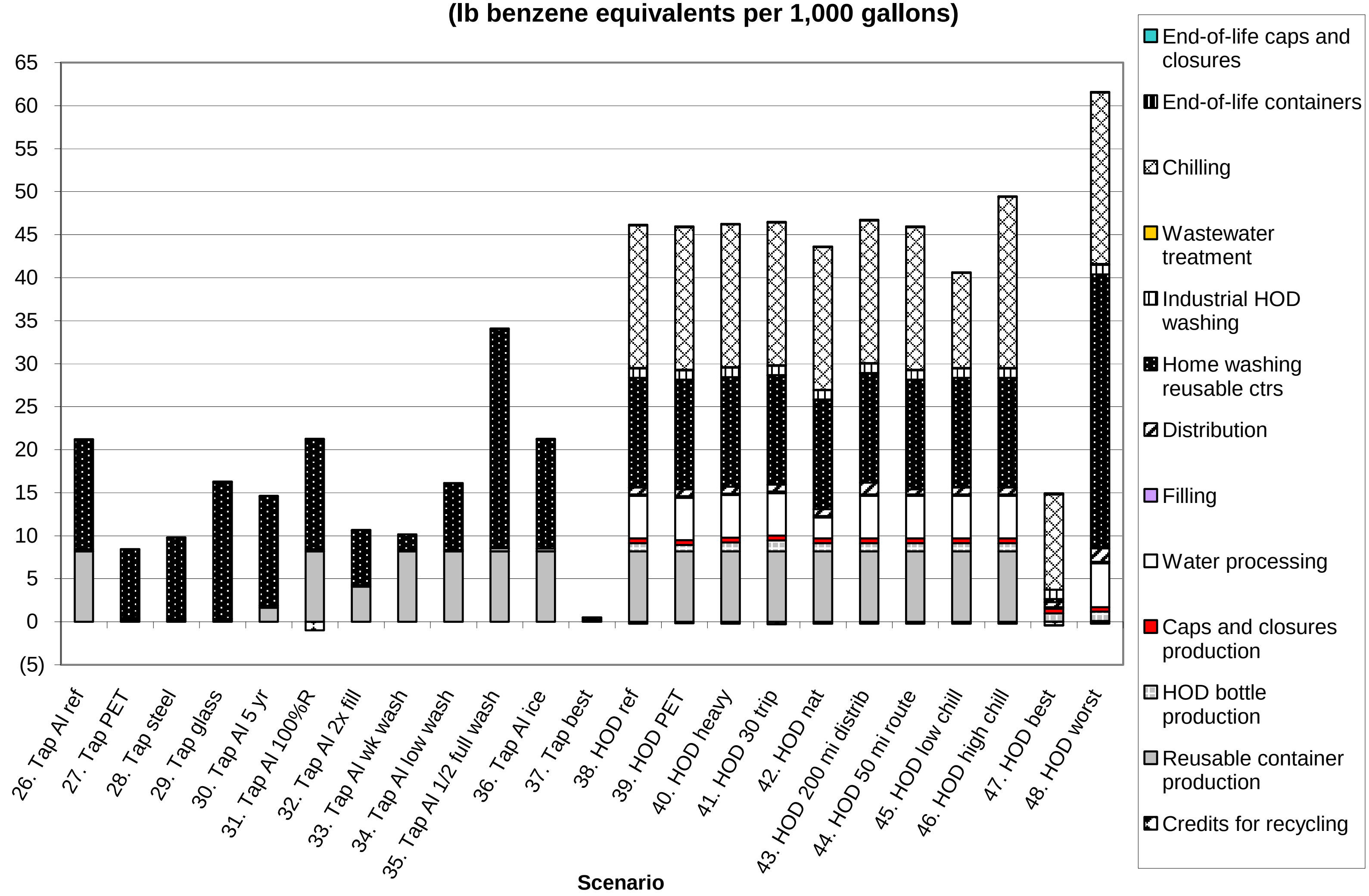


Table 3-3. Ecotoxicity Potential by Life Cycle Stage for Drinking Water System Scenarios (page 1 of 2)
(lb 2,4 D equivalents per 1,000 gallons)*

	Bottled Water												
	PET ref R1	PET ref R2	PET ref R3	PET 1 liter	PET 8 oz	PET light	PET light, low mold	25% rPET R1	25% rPET R2	25% rPET R3	PLA 0 decomp	PLA 100 decomp	PLA compost
Bottled Water Scenarios	1	2	3	4	5	6	7	8	9	10	11	12	13
Production													
Disposable bottle	153	153	153	226	300	113	113	136	119	153	44.5	44.5	44.5
Caps and closures	16.1	16.1	16.1	14.0	29.7	14.0	14.0	16.1	16.1	16.1	16.1	16.1	16.1
Secondary packaging	21.8	21.8	21.8	10.9	46.2	21.8	21.8	21.8	21.8	21.8	21.8	21.8	21.8
Processes													
Water processing	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51
Filling	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058
Distribution	12.1	12.1	12.1	12.2	12.5	12.0	12.0	12.1	12.1	12.1	12.1	12.1	12.1
Consumer transport	15.1	15.1	15.1	7.59	31.8	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
Wastewater treatment	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058
Chilling	0	0	0	0	0	0	0	0	0	0	0	0	0
End of life management													
Containers	8.01	1.13	13.0	11.8	15.6	5.90	5.90	7.75	1.13	13.0	3.10	1.94	2.43
Caps and closures	0.34	0.34	0.34	0.30	0.64	0.30	0.30	0.34	0.34	0.34	0.34	0.34	0.34
Secondary packaging	0.41	0.22	0.46	0.20	0.86	0.41	0.41	0.41	0.22	0.46	0.41	0.41	0.41
Credits for recycling	-16.2	0	-32.0	-19.7	-32.4	-13.1	-13.1	-14.7	0	-32.0	-4.26	-4.26	-4.26
TOTAL	**213**	**222**	**202**	**264**	**406**	**171**	**171**	**197**	**187**	**202**	**111**	**109.6**	**110.1**

	Bottled Water											
	PET nat	PET Maine nat	PET Fiji nat	PET Fiji free sea	Glass France	PET 500 mi empty	PET 100% store trip	PET refrig	PET 37%R	PET best	PET worst	PLA best
Bottled Water Scenarios	14	15	16	17	18	19	20	21	22	23	24	25
Production												
Disposable bottle	153	157	325	325	360	181	153	153	153	113	335	32.6
Caps and closures	16.1	16.1	26.1	26.1	189	16.1	16.1	16.1	16.1	14.0	29.7	14.0
Secondary packaging	21.8	21.8	21.8	21.8	30.5	21.8	21.8	21.8	21.8	11.0	50.5	11.0
Processes												
Water processing	0.72	1.78	0.0027	0.0027	1.93	1.51	1.51	1.51	1.51	0.0011	1.98	0.0011
Filling	0.058	0.14	0.14	0.14	0.16	0.058	0.058	0.058	0.058	0.058	0.14	0.058
Distribution	31.4	791	463	230	1,436	12.1	12.1	12.1	12.1	4.79	819	4.79
Consumer transport	15.1	15.1	15.1	15.1	21.1	15.1	375	15.1	15.1	0.10	791	0.10
Wastewater treatment	0	0	0	0	0	0.0058	0.0058	0.0058	0.0058	0	2.3E-04	0
Chilling	0	0	0	0	0	0	0	0.84	0	0	3.54	0
End of life management												
Containers	8.01	8.01	16.6	16.6	24.9	8.01	8.01	8.01	5.98	14.2	5.80	2.28
Caps and closures	0.34	0.34	0.56	0.56	4.06	0.34	0.34	0.34	0.34	0.30	0.64	0.30
Secondary packaging	0.41	0.41	0.41	0.41	0.57	0.41	0.41	0.41	0.41	0.18	0.94	0.18
Credits for recycling	-16.2	-16.2	-29.0	-29.0	-138	-16.2	-16.2	-16.2	-11.4	-28.0	-9.86	0
TOTAL	**231**	**995**	**840**	**607**	**1,930**	**240**	**572**	**213**	**215**	**130**	**2,028**	**65.3**

* Does not include ecotoxicity potential for production or runoff of agricultural chemicals.

Table 3-3. Ecotoxicity Potential by Life Cycle Stage for Drinking Water System Scenarios (page 2 of 2)
(lb 2,4 D equivalents per 1,000 gallons)*

	Tap											
Tap Water Scenarios	Tap Al ref 26	Tap PET 27	Tap steel 28	Tap glass 29	Tap Al 5 yr 30	Tap Al 100%R 31	Tap Al 2x fill 32	Tap Al wk wash 33	Tap Al low wash 34	Tap Al 1/2 full wash 35	Tap Al ice 36	Tap best 37
Production												
Reusable drinking container	3.75	1.86	1.07	0.75	0.75	3.75	1.87	3.75	3.75	3.75	3.75	0.19
Caps and closures	0.29	0.26	0.63	0	0.058	0.29	0.15	0.29	0.29	0.29	0.29	0.026
Processes												
Water processing	0.081	0.068	0.072	0.090	0.081	0.081	0.063	0.050	0.055	0.12	0.10	0.045
Home washing of reusable container	7.30	4.56	5.41	9.12	7.30	7.30	3.65	1.04	3.37	14.6	7.30	0.15
Wastewater treatment	0.019	0.012	0.014	0.024	0.019	0.019	0.0095	0.0027	0.0055	0.038	0.019	2.4E-04
Chilling	0	0	0	0	0	0	0	0	0	0	0	0
End of life management												
Containers	0.047	0.034	0.060	0.039	0.0093	0.17	0.023	0.047	0.047	0.047	0.047	0.0034
Caps and closures	0.0062	0.0056	0.014	0	0.0012	0.0062	0.0031	0.0062	0.0062	0.0062	0.0062	5.6E-04
Credits for recycling	0	0	0	0	0	-1.62	0	0	0	0	0	0
TOTAL	**11.5**	**6.80**	**7.27**	**10.0**	**8.22**	**10.0**	**5.77**	**5.18**	**7.52**	**18.8**	**11.5**	**0.41**

	HOD										
HOD Water Scenarios	HOD ref 38	HOD PET 39	HOD heavy 40	HOD 30 trip 41	HOD nat 42	HOD 200 mi distrib 43	HOD 50 mi route 44	HOD low chill 45	HOD high chill 46	HOD best 47	HOD worst 48
Production											
Reusable drinking container	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	0.19	0.75
HOD bottle	4.15	6.11	4.56	5.53	4.15	4.15	4.15	4.15	4.15	4.15	8.95
Caps and closures	3.32	3.32	3.32	3.32	3.32	3.32	3.32	3.32	3.32	3.06	3.03
Processes											
Water processing	1.55	1.55	1.55	1.55	0.76	1.55	1.55	1.55	1.55	0.0045	1.61
Filling	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058
Distribution	51.2	51.2	51.3	51.2	51.2	87.6	38.1	51.2	51.2	38.1	101
Home washing of reusable container	7.30	7.30	7.30	7.30	7.30	7.30	7.30	7.30	7.30	0.15	18.2
Industrial HOD washing	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Wastewater treatment	0.026	0.026	0.026	0.026	0.021	0.026	0.026	0.026	0.026	0.0018	0.055
Chilling	5.15	5.15	5.15	5.15	5.15	5.15	5.15	3.44	6.18	3.44	6.18
End of life management											
Containers	0.16	0.16	0.17	0.20	0.16	0.16	0.16	0.16	0.16	0.12	0.21
Caps and closures	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.080	0.080
Credits for recycling	-1.79	-2.75	-1.97	-2.39	-1.79	-1.79	-1.79	-1.79	-1.79	-3.59	-4.03
TOTAL	**75.3**	**76.3**	**75.8**	**76.2**	**74.5**	**112**	**62.3**	**73.6**	**76.4**	**46.2**	**137**

* Does not include ecotoxicity potential for production or runoff of agricultural chemicals.
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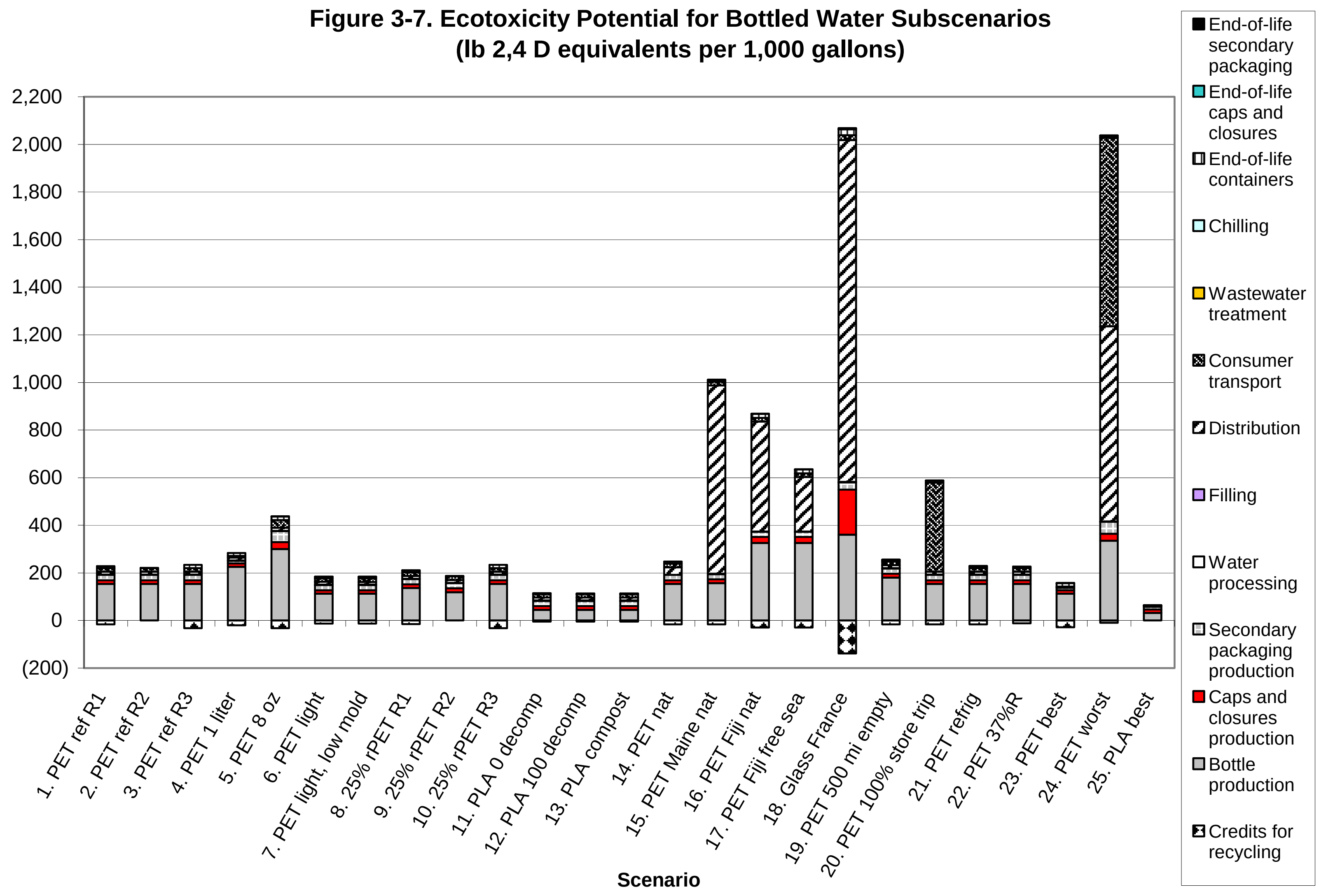
Figure 3-7. Ecotoxicity Potential for Bottled Water Subscenarios
(lb 2,4 D equivalents per 1,000 gallons)
2,200
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
(200)
1. PET ref R1
2. PET ref R2
3. PET ref R3
4. PET 1 liter
5. PET 8 oz
6. PET light
7. PET light, low mold
8. 25% rPET R1
9. 25% rPET R2
10. 25% rPET R3
11. PLA 0 decomp
12. PLA 100 decomp
13. PLA compost
14. PET nat
15. PET Maine nat
16. PET Fiji nat
17. PET Fiji free sea
18. Glass France
19. PET 500 mi empty
20. PET 100% store trip
21. PET refrig
22. PET 37%R
23. PET best
24. PET worst
25. PLA best
Scenario
End-of-life secondary packaging
End-of-life caps and closures
End-of-life containers
Chilling
Wastewater treatment
Consumer transport
Distribution
Filling
Water processing
Secondary packaging production
Caps and closures production
Bottle production
Credits for recycling

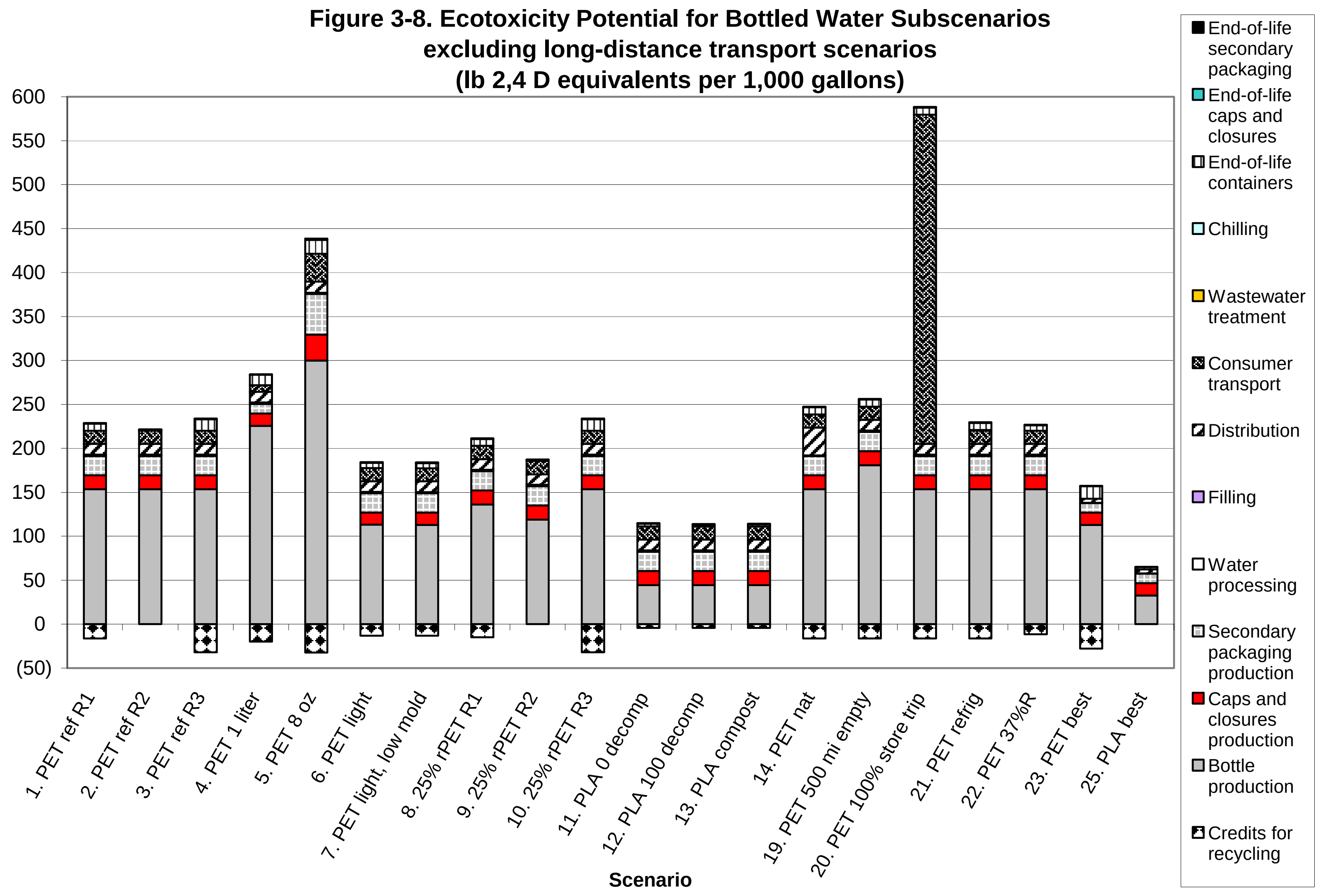
Figure 3-8. Ecotoxicity Potential for Bottled Water Subscenarios
excluding long-distance transport scenarios
(lb 2,4 D equivalents per 1,000 gallons)
600
550
500
450
400
350
300
250
200
150
100
50
0
(50)
1. PET ref R1
2. PET ref R2
3. PET ref R3
4. PET 1 liter
5. PET 8 oz
6. PET light
7. PET light, low mold
8. 25% rPET R1
9. 25% rPET R2
10. 25% rPET R3
11. PLA 0 decomp
12. PLA 100 decomp
13. PLA compost
14. PET nat
19. PET 500 mi empty
20. PET 100% store trip
21. PET refrig
22. PET 37%R
23. PET best
25. PLA best
Scenario
End-of-life secondary packaging
End-of-life caps and closures
End-of-life containers
Chilling
Wastewater treatment
Consumer transport
Distribution
Filling
Water processing
Secondary packaging production
Caps and closures production
Bottle production
Credits for recycling

Figure 3-9. Ecotoxicity Potential for Tap and HOD Water Subscenarios (lb 2,4 D equivalents per 1,000 gallons)

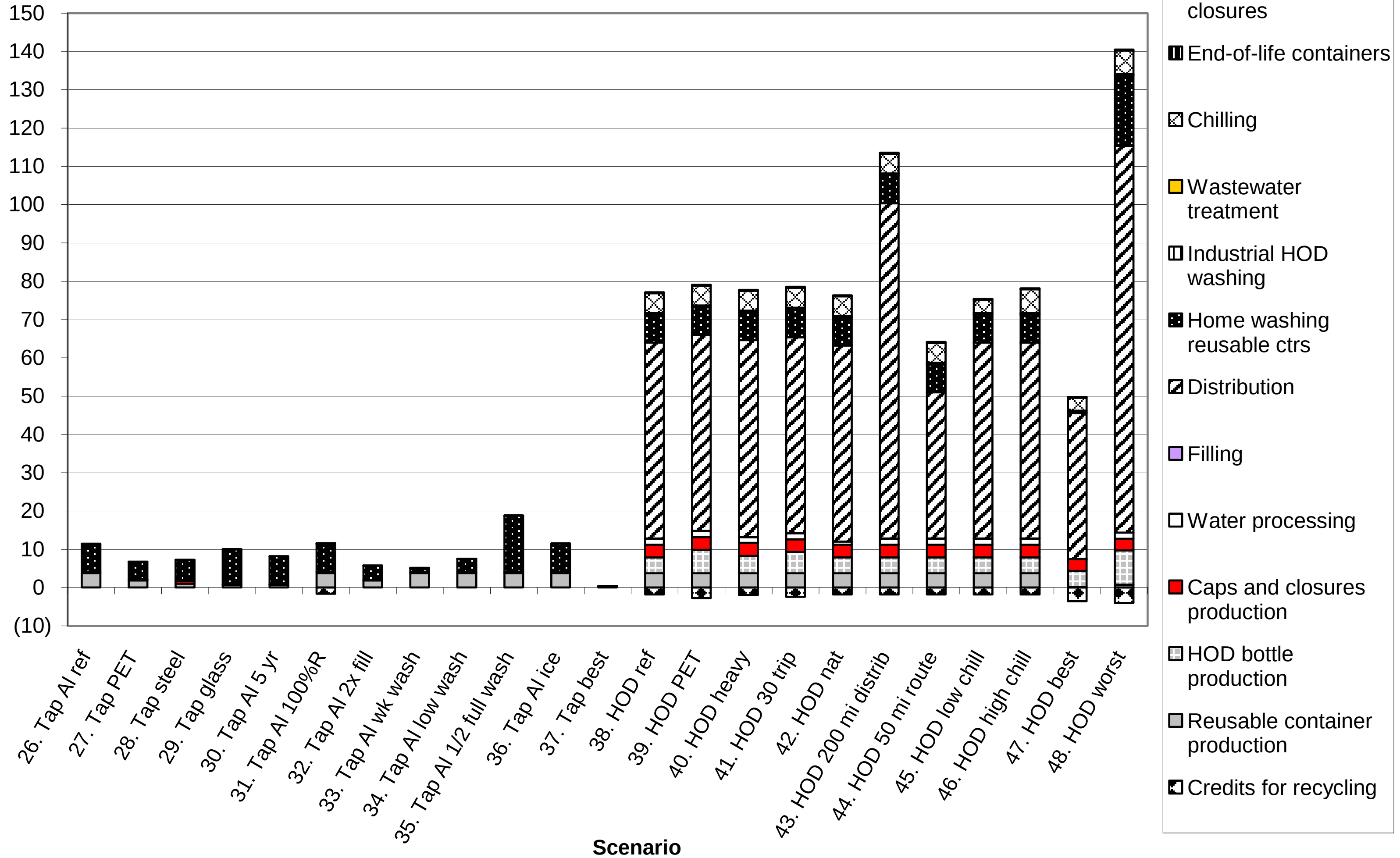

Table 3-4. Eutrophication Potential by Life Cycle Stage for Drinking Water System Scenarios (page 1 of 2)
(lb N equivalents per 1,000 gallons)*

	Bottled Water												
	PET ref R1	PET ref R2	PET ref R3	PET 1 liter	PET 8 oz	PET light	PET light, low mold	25% rPET R1	25% rPET R2	25% rPET R3	PLA 0 decomp	PLA 100 decomp	PLA compost
Bottled Water Scenarios	1	2	3	4	5	6	7	8	9	10	11	12	13
Production													
Disposable bottle	0.13	0.13	0.13	0.20	0.26	0.098	0.096	0.12	0.11	0.13	0.71	0.71	0.71
Caps and closures	0.013	0.013	0.013	0.011	0.024	0.011	0.011	0.013	0.013	0.013	0.013	0.013	0.013
Secondary packaging	0.062	0.062	0.062	0.031	0.13	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062
Processes													
Water processing	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
Filling	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04
Distribution	0.013	0.013	0.013	0.014	0.014	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
Consumer transport	0.0047	0.0047	0.0047	0.0024	0.010	0.0047	0.0047	0.0047	0.0047	0.0047	0.0047	0.0047	0.0047
Wastewater treatment	3.6E-05	3.6E-05	3.6E-05	3.6E-05	3.6E-05	3.6E-05	3.6E-05	3.6E-05	3.6E-05	3.6E-05	3.6E-05	3.6E-05	3.6E-05
Chilling	0	0	0	0	0	0	0	0	0	0	0	0	0
End of life management													
Containers	0.023	5.9E-04	0.045	0.034	0.046	0.017	0.017	0.023	5.9E-04	0.045	0.0018	-0.0067	0.0016
Caps and closures	9.3E-05	9.3E-05	9.3E-05	8.1E-05	1.7E-04	8.1E-05	8.1E-05	9.3E-05	9.3E-05	9.3E-05	9.3E-05	9.3E-05	9.3E-05
Secondary packaging	-8.8E-05	-1.1E-04	1.3E-04	-4.4E-05	-1.9E-04	-8.8E-05	-8.8E-05	-8.8E-05	-1.1E-04	1.3E-04	-8.8E-05	-8.8E-05	-8.8E-05
Credits for recycling	-0.042	0	-0.083	-0.041	-0.085	-0.036	-0.036	-0.039	0	-0.083	-0.021	-0.021	-0.021
TOTAL	**0.22**	**0.24**	**0.20**	**0.26**	**0.41**	**0.18**	**0.18**	**0.21**	**0.22**	**0.20**	**0.80**	**0.79**	**0.80**

	Bottled Water											
	PET nat	PET Maine nat	PET Fiji nat	PET Fiji free sea	Glass France	PET 500 mi empty	PET 100% store trip	PET refrig	PET 37%R	PET best	PET worst	PLA best
Bottled Water Scenarios	14	15	16	17	18	19	20	21	22	23	24	25
Production												
Disposable bottle	0.13	0.14	0.29	0.29	1.02	0.16	0.13	0.13	0.13	0.096	0.30	0.52
Caps and closures	0.013	0.013	0.021	0.021	0.15	0.013	0.013	0.013	0.013	0.011	0.024	0.011
Secondary packaging	0.062	0.062	0.062	0.062	0.086	0.062	0.062	0.062	0.062	0.0065	0.14	0.0065
Processes												
Water processing	0.0053	0.0071	1.1E-05	1.1E-05	0.0046	0.011	0.011	0.011	0.011	7.9E-06	0.0079	7.9E-06
Filling	4.3E-04	5.7E-04	5.7E-04	5.7E-04	3.7E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	5.7E-04	4.3E-04
Distribution	0.035	0.88	1.73	0.25	2.88	0.013	0.013	0.013	0.013	0.0053	0.91	0.0053
Consumer transport	0.0047	0.0047	0.0047	0.0047	0.0066	0.0047	0.12	0.0047	0.0047	3.2E-05	0.25	3.2E-05
Wastewater treatment	0	0	0	0	0	3.6E-05	3.6E-05	3.6E-05	3.6E-05	0	1.5E-06	0
Chilling	0	0	0	0	0	0	0	0.0062	0	0	0.026	0
End of life management												
Containers	0.023	0.023	0.048	0.048	0.045	0.023	0.023	0.023	0.015	0.053	0.0030	0.0013
Caps and closures	9.3E-05	9.3E-05	1.5E-04	1.5E-04	0.0011	9.3E-05	9.3E-05	9.3E-05	9.3E-05	8.1E-05	1.7E-04	8.1E-05
Secondary packaging	-8.8E-05	-8.8E-05	-8.8E-05	-8.8E-05	-1.2E-04	-8.8E-05	-8.8E-05	-8.8E-05	-8.8E-05	-5.0E-05	-2.0E-04	-5.0E-05
Credits for recycling	-0.042	-0.042	-0.064	-0.064	-0.42	-0.042	-0.042	-0.042	-0.034	-0.048	-0.049	0
TOTAL	**0.23**	**1.08**	**2.09**	**0.61**	**3.77**	**0.25**	**0.33**	**0.22**	**0.22**	**0.12**	**1.61**	**0.55**

* Does not include eutrophication potential for production or runoff of agricultural chemicals.

Table 3-4. Eutrophication Potential by Life Cycle Stage for Drinking Water System Scenarios (page 2 of 2)
(lb N equivalents per 1,000 gallons)*

	Tap											
Tap Water Scenarios	Tap Al ref 26	Tap PET 27	Tap steel 28	Tap glass 29	Tap Al 5 yr 30	Tap Al 100%R 31	Tap Al 2x fill 32	Tap Al wk wash 33	Tap Al low wash 34	Tap Al 1/2 full wash 35	Tap Al ice 36	Tap best 37
Production												
Reusable drinking container	0.0095	0.0017	0.0040	0.0022	0.0019	0.0095	0.0047	0.0095	0.0095	0.0095	0.0095	1.7E-04
Caps and closures	2.3E-04	2.1E-04	5.1E-04	0	4.6E-05	2.3E-04	1.2E-04	2.3E-04	2.3E-04	2.3E-04	2.3E-04	2.1E-05
Processes												
Water processing	5.2E-04	4.3E-04	4.6E-04	5.8E-04	5.2E-04	5.2E-04	4.0E-04	3.2E-04	3.5E-04	7.5E-04	6.6E-04	2.9E-04
Home washing of reusable container	0.032	0.020	0.023	0.040	0.032	0.032	0.016	0.0045	0.018	0.063	0.032	8.3E-04
Wastewater treatment	1.2E-04	7.4E-05	8.8E-05	1.5E-04	1.2E-04	1.2E-04	5.9E-05	1.7E-05	3.4E-05	2.4E-04	1.2E-04	1.5E-06
Chilling	0	0	0	0	0	0	0	0	0	0	0	0
End of life management												
Containers	3.7E-05	1.8E-05	5.2E-05	3.9E-05	7.3E-06	2.4E-04	1.8E-05	3.7E-05	3.7E-05	3.7E-05	3.7E-05	1.8E-06
Caps and closures	1.7E-06	1.5E-06	3.7E-06	0	3.4E-07	1.7E-06	8.4E-07	1.7E-06	1.7E-06	1.7E-06	1.7E-06	1.5E-07
Credits for recycling	0	0	0	0	0	-0.0036	0	0	0	0	0	0
TOTAL	**0.042**	**0.022**	**0.029**	**0.043**	**0.034**	**0.039**	**0.021**	**0.015**	**0.029**	**0.074**	**0.042**	**0.0013**

	HOD										
HOD Water Scenarios	HOD ref 38	HOD PET 39	HOD heavy 40	HOD 30 trip 41	HOD nat 42	HOD 200 mi distrib 43	HOD 50 mi route 44	HOD low chill 45	HOD high chill 46	HOD best 47	HOD worst 48
Production											
Reusable drinking container	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	1.7E-04	0.0022
HOD bottle	0.021	0.0057	0.023	0.028	0.021	0.021	0.021	0.021	0.021	0.021	0.0084
Caps and closures	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0027	0.0026
Processes											
Water processing	0.011	0.011	0.011	0.011	0.0056	0.011	0.011	0.011	0.011	2.9E-05	0.012
Filling	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04
Distribution	0.050	0.050	0.050	0.050	0.050	0.090	0.038	0.050	0.050	0.038	0.10
Home washing of reusable container	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	8.3E-04	0.079
Industrial HOD washing	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026
Wastewater treatment	1.6E-04	1.6E-04	1.6E-04	1.6E-04	1.3E-04	1.6E-04	1.6E-04	1.6E-04	1.6E-04	1.1E-05	3.4E-04
Chilling	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.025	0.046	0.025	0.046
End of life management											
Containers	2.9E-04	3.1E-04	3.2E-04	3.8E-04	2.9E-04	2.9E-04	2.9E-04	2.9E-04	2.9E-04	4.8E-04	4.4E-04
Caps and closures	2.3E-05	2.3E-05	2.3E-05	2.3E-05	2.3E-05	2.3E-05	2.3E-05	2.3E-05	2.3E-05	2.2E-05	2.1E-05
Credits for recycling	-0.0096	-0.0020	-0.011	-0.013	-0.0096	-0.0096	-0.0096	-0.0096	-0.0096	-0.019	-0.0030
TOTAL	**0.16**	**0.15**	**0.16**	**0.16**	**0.15**	**0.20**	**0.15**	**0.15**	**0.17**	**0.072**	**0.25**

* Does not include eutrophication potential for production or runoff of agricultural chemicals.
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Figure 3-10. Eutrophication Potential for Bottled Water Subscenarios (lb nitrogen equivalents per 1,000 gallons)

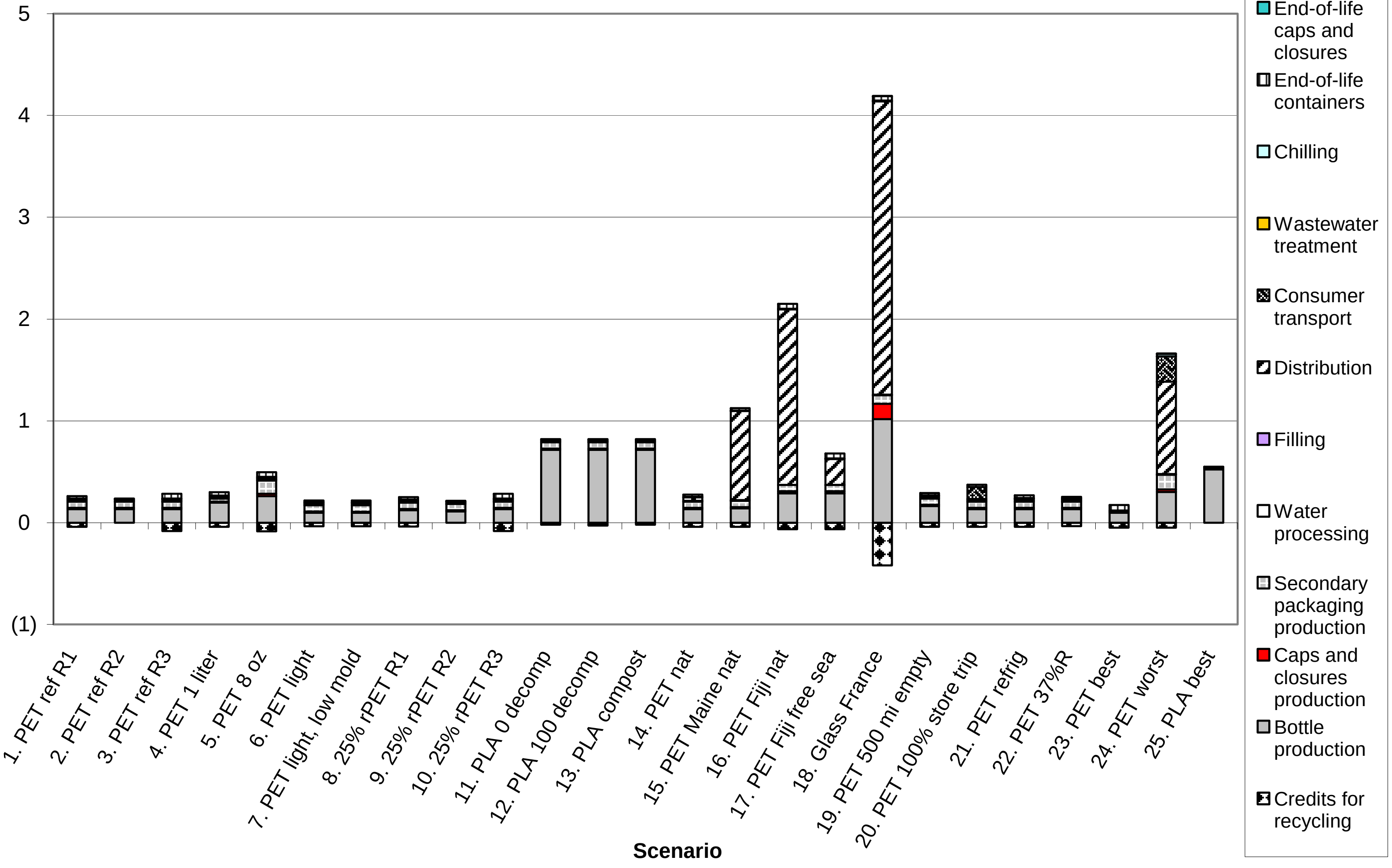

Figure 3-11. Eutrophication Potential for Bottled Water Subscenarios excluding long-distance transport scenarios (lb nitrogen equivalents per 1,000 gallons)

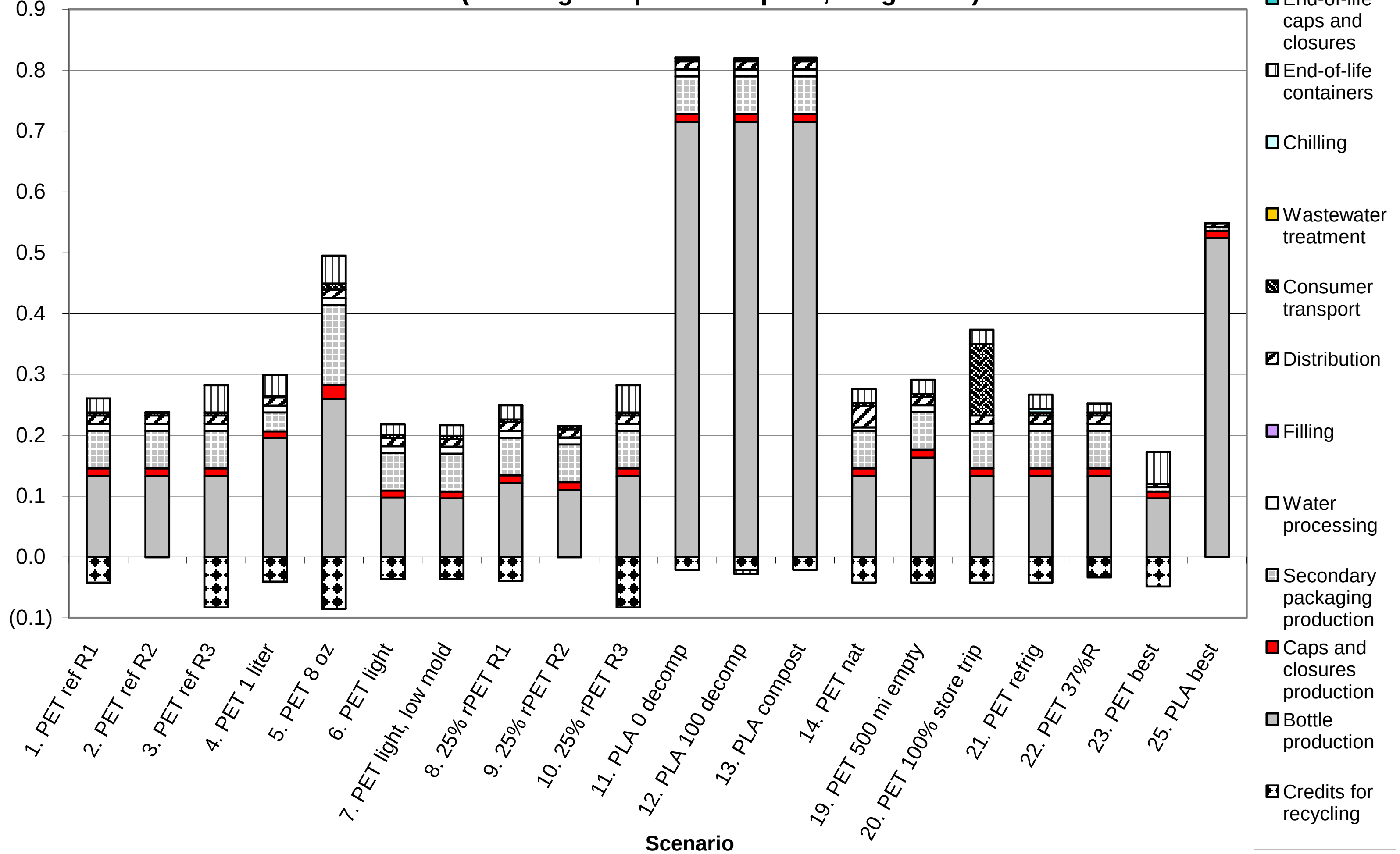

Figure 3-12. Eutrophication Potential for Tap and HOD Water Subscenarios (lb nitrogen equivalents per 1,000 gallons)

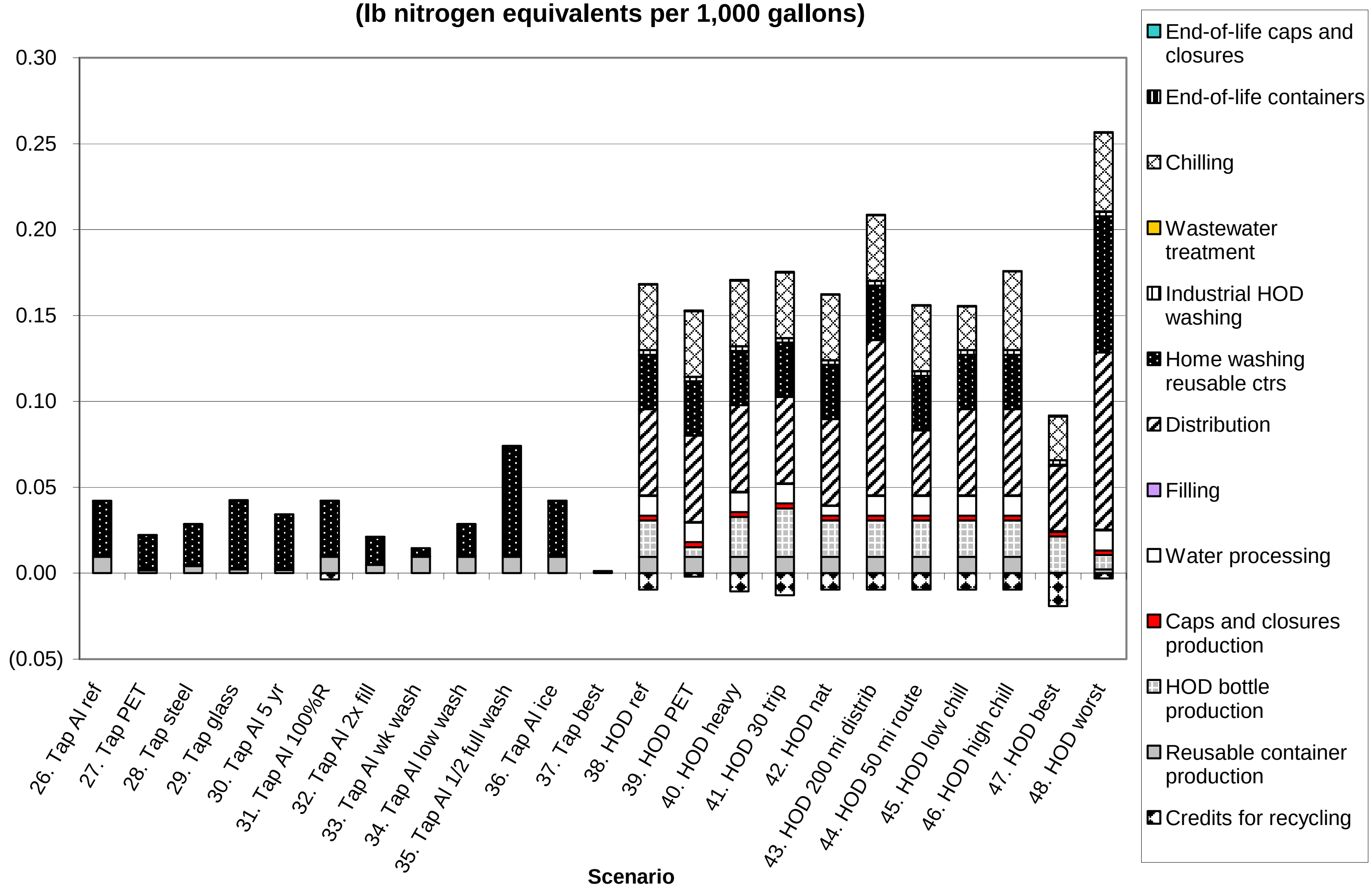

Table 3-5. Global Warming Potential by Life Cycle Stage for Drinking Water System Scenarios (page 1 of 2)
(lb CO2 equivalents per 1,000 gallons)

	Bottled Water												
	PET ref R1	PET ref R2	PET ref R3	PET 1 liter	PET 8 oz	PET light	PET light, low mold	25% rPET R1	25% rPET R2	25% rPET R3	PLA 0 decomp	PLA 100 decomp	PLA compost
Bottled Water Scenarios	1	2	3	4	5	6	7	8	9	10	11	12	13
Production													
Disposable bottle	774	774	774	1,138	1,512	570	559	716	657	774	818	818	818
Caps and closures	96.6	96.6	96.6	84.6	179	84.6	84.6	96.6	96.6	96.6	96.6	96.6	96.6
Secondary packaging	108	108	108	54.2	229	108	108	108	108	108	108	108	108
Processes													
Water processing	87.8	87.8	87.8	87.8	87.8	87.8	87.8	87.8	87.8	87.8	87.8	87.8	87.8
Filling	3.39	3.39	3.39	3.39	3.39	3.39	3.39	3.39	3.39	3.39	3.39	3.39	3.39
Distribution	60.2	60.2	60.2	60.7	62.2	59.7	59.7	60.2	60.2	60.2	60.2	60.2	60.2
Consumer transport	78.2	78.2	78.2	39.4	165	78.2	78.2	78.2	78.2	78.2	78.2	78.2	78.2
Wastewater treatment	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Chilling	0	0	0	0	0	0	0	0	0	0	0	0	0
End of life management													
Containers	87.3	15.9	133	128	171	64.3	64.3	83.7	15.9	133	-382	564	5.36
Caps and closures	5.90	5.90	5.90	5.16	10.9	5.16	5.16	5.90	5.90	5.90	5.90	5.90	5.90
Secondary packaging	7.74	5.41	6.65	3.87	16.3	7.74	7.74	7.74	5.41	6.65	7.74	7.74	7.74
Credits for recycling	-189	0	-372	-259	-372	-144	-144	-168	0	-372	-19.3	-19.3	-19.3
TOTAL	**1,121**	**1,236**	**982**	**1,347**	**2,064**	**926**	**915**	**1,080**	**1,119**	**982**	**865**	**1,811**	**1253**

	Bottled Water											
	PET nat	PET Maine nat	PET Fiji nat	PET Fiji free sea	Glass France	PET 500 mi empty	PET 100% store trip	PET refrig	PET 37%R	PET best	PET worst	PLA best
Bottled Water Scenarios	14	15	16	17	18	19	20	21	22	23	24	25
Production												
Disposable bottle	774	832	1,721	1,721	4,129	910	774	774	774	559	1,763	591
Caps and closures	96.6	96.6	157	157	1,139	96.6	96.6	96.6	96.6	84.6	179	84.6
Secondary packaging	108	108	108	108	151	108	108	108	108	59.4	250	59.4
Processes												
Water processing	42.0	58.0	0.087	0.087	37.2	87.8	87.8	87.8	87.8	0.063	64.5	0.063
Filling	3.39	4.68	4.68	4.68	3.00	3.39	3.39	3.39	3.39	3.39	4.68	3.39
Distribution	156	3,933	2,382	1,142	7,106	60.2	60.2	60.2	60.2	23.8	4,074	23.8
Consumer transport	78.2	78.2	78.2	78.2	109	78.2	1,942	78.2	78.2	0.52	4,101	0.52
Wastewater treatment	0	0	0	0	0	0.30	0.30	0.30	0.30	0	0.012	0
Chilling	0	0	0	0	0	0	0	49.0	0	0	207	0
End of life management												
Containers	87.3	87.3	181	181	222	87.3	87.3	87.3	69.0	139	81.9	-281
Caps and closures	5.90	5.90	9.58	9.58	69.5	5.90	5.90	5.90	5.90	5.16	10.9	5.16
Secondary packaging	7.74	7.74	7.74	7.74	10.8	7.74	7.74	7.74	7.74	4.47	17.9	4.47
Credits for recycling	-189	-189	-370	-370	-1,675	-189	-189	-189	-121	-397	-44.7	0
TOTAL	**1,171**	**5,023**	**4,279**	**3,040**	**11,302**	**1,257**	**2,985**	**1,170**	**1,171**	**483**	**10,709**	**491**

Table 3-5. Global Warming Potential by Life Cycle Stage for Drinking Water System Scenarios (page 2 of 2)
(lb CO2 equivalents per 1,000 gallons)

	Tap											
Tap Water Scenarios	Tap Al ref 26	Tap PET 27	Tap steel 28	Tap glass 29	Tap Al 5 yr 30	Tap Al 100%R 31	Tap Al 2x fill 32	Tap Al wk wash 33	Tap Al low wash 34	Tap Al 1/2 full wash 35	Tap Al ice 36	Tap best 37
Production												
Reusable drinking container	56.4	10.6	36.0	9.35	11.3	56.4	28.2	56.4	56.4	56.4	56.4	1.06
Caps and closures	1.75	1.57	3.82	0	0.35	1.75	0.87	1.75	1.75	1.75	1.75	0.16
Processes												
Water processing	4.18	3.48	3.69	4.65	4.18	4.18	3.24	2.57	2.84	6.05	5.33	2.33
Home washing of reusable container	276	172	204	345	276	276	138	39.4	153	551	276	6.85
Wastewater treatment	0.97	0.61	0.72	1.22	0.97	0.97	0.49	0.14	0.28	1.94	0.97	0.012
Chilling	0	0	0	0	0	0	0	0	0	0	0	0
End of life management												
Containers	0.22	0.47	0.29	0.19	0.045	2.40	0.11	0.22	0.22	0.22	0.22	0.047
Caps and closures	0.11	0.096	0.23	0	0.021	0.11	0.053	0.11	0.11	0.11	0.11	0.0096
Credits for recycling	0	0	0	0	0	-27.0	0	0	0	0	0	0
TOTAL	**339**	**189**	**249**	**360**	**293**	**315**	**171**	**101**	**215**	**618**	**340**	**10.5**

	HOD										
HOD Water Scenarios	HOD ref 38	HOD PET 39	HOD heavy 40	HOD 30 trip 41	HOD nat 42	HOD 200 mi distrib 43	HOD 50 mi route 44	HOD low chill 45	HOD high chill 46	HOD best 47	HOD worst 48
Production											
Reusable drinking container	56.4	56.4	56.4	56.4	56.4	56.4	56.4	56.4	56.4	1.06	9.35
HOD bottle	63.6	35.0	70.0	84.8	63.6	63.6	63.6	63.6	63.6	63.6	51.3
Caps and closures	24.9	24.9	24.9	24.9	24.9	24.9	24.9	24.9	24.9	23.3	23.2
Processes											
Water processing	89.8	89.8	89.8	89.8	44.0	89.8	89.8	89.8	89.8	0.23	92.6
Filling	3.39	3.39	3.39	3.39	3.39	3.39	3.39	3.39	3.39	3.39	3.39
Distribution	255	255	256	255	255	436	190	255	255	190	503
Home washing of reusable container	276	276	276	276	276	276	276	276	276	6.85	689
Industrial HOD washing	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9
Wastewater treatment	1.35	1.35	1.35	1.35	1.05	1.35	1.35	1.35	1.35	0.091	2.81
Chilling	301	301	301	301	301	301	301	201	361	201	361
End of life management											
Containers	3.03	2.98	3.31	3.96	3.03	3.03	3.03	3.03	3.03	4.00	4.24
Caps and closures	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.37	1.36
Credits for recycling	-24.5	-11.3	-27.0	-32.7	-24.5	-24.5	-24.5	-24.5	-24.5	-49.0	-16.5
TOTAL	**1,072**	**1,057**	**1,077**	**1,086**	**1,026**	**1,253**	**1,007**	**972**	**1,132**	**467**	**1,746**

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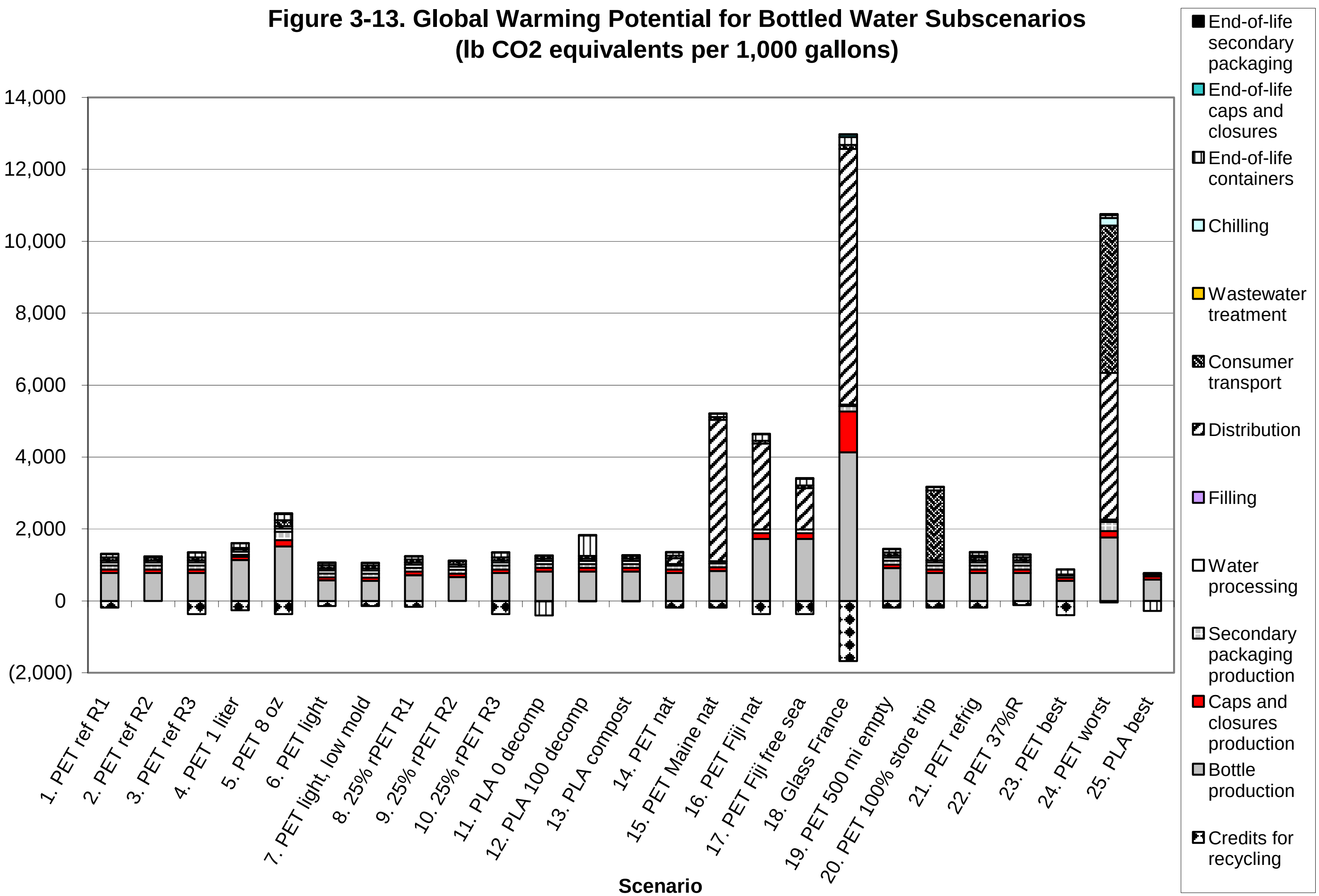
Figure 3-13. Global Warming Potential for Bottled Water Subscenarios
(lb CO2 equivalents per 1,000 gallons)
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
(2,000)
1. PET ref R1
2. PET ref R2
3. PET ref R3
4. PET 1 liter
5. PET 8 oz
6. PET light
7. PET light, low mold
8. 25% rPET R1
9. 25% rPET R2
10. 25% rPET R3
11. PLA 0 decomp
12. PLA 100 decomp
13. PLA compost
14. PET nat
15. PET Maine nat
16. PET Fiji nat
17. PET Fiji free sea
18. Glass France
19. PET 500 mi empty
20. PET 100% store trip
21. PET refrig
22. PET 37%R
23. PET best
24. PET worst
25. PLA best
Scenario
End-of-life secondary packaging
End-of-life caps and closures
End-of-life containers
Chilling
Wastewater treatment
Consumer transport
Distribution
Filling
Water processing
Secondary packaging production
Caps and closures production
Bottle production
Credits for recycling

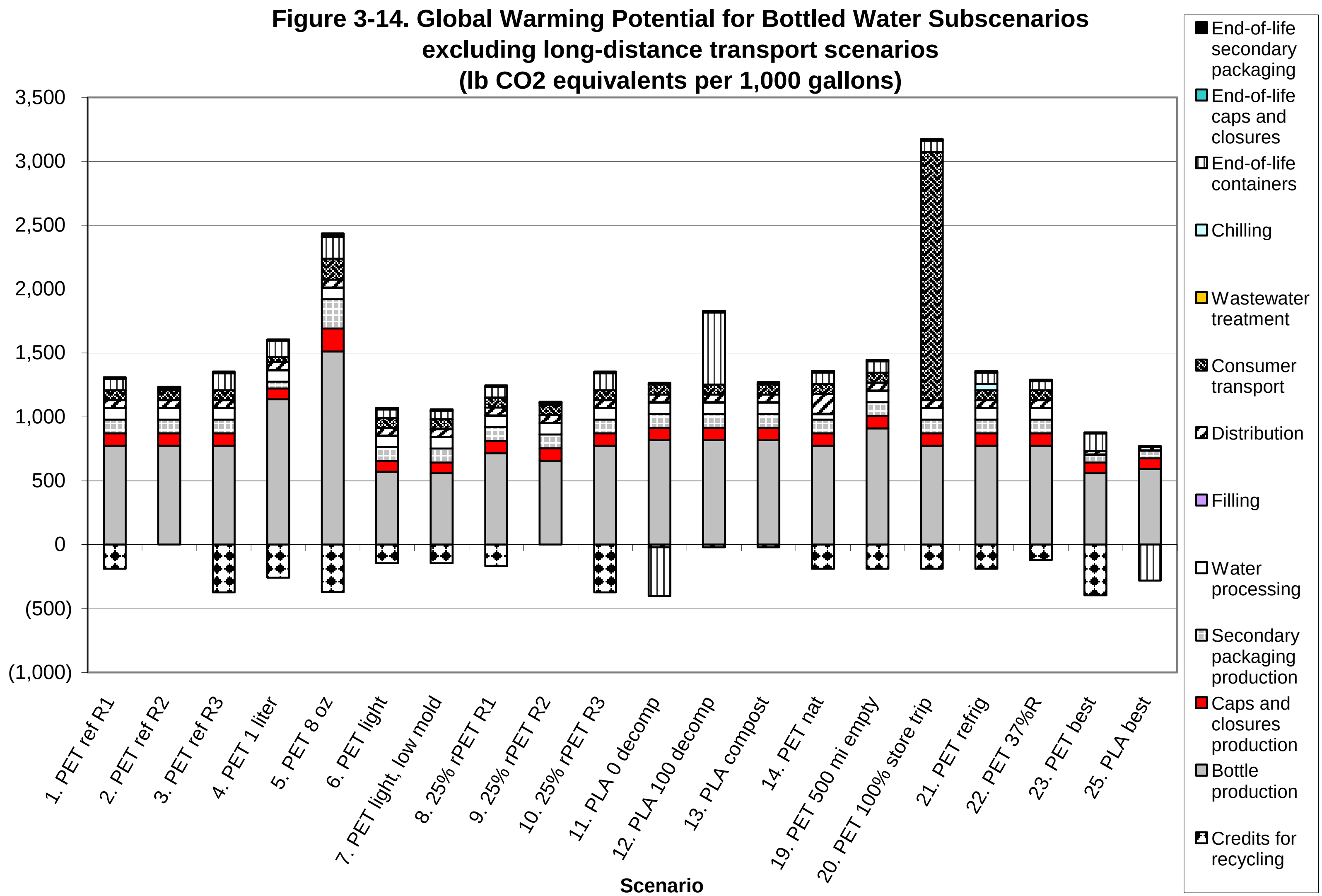

Figure 3-14. Global Warming Potential for Bottled Water Subscenarios
excluding long-distance transport scenarios
(lb CO2 equivalents per 1,000 gallons)
3,500
3,000
2,500
2,000
1,500
1,000
500
0
(500)
(1,000)
1. PET ref R1
2. PET ref R2
3. PET ref R3
4. PET 1 liter
5. PET 8 oz
6. PET light
7. PET light, low mold
8. 25% rPET R1
9. 25% rPET R2
10. 25% rPET R3
11. PLA 0 decomp
12. PLA 100 decomp
13. PLA compost
14. PET nat
19. PET 500 mi empty
20. PET 100% store trip
21. PET refrig
22. PET 37%R
23. PET best
25. PLA best
Scenario
End-of-life secondary packaging
End-of-life caps and closures
End-of-life containers
Chilling
Wastewater treatment
Consumer transport
Distribution
Filling
Water processing
Secondary packaging production
Caps and closures production
Bottle production
Credits for recycling

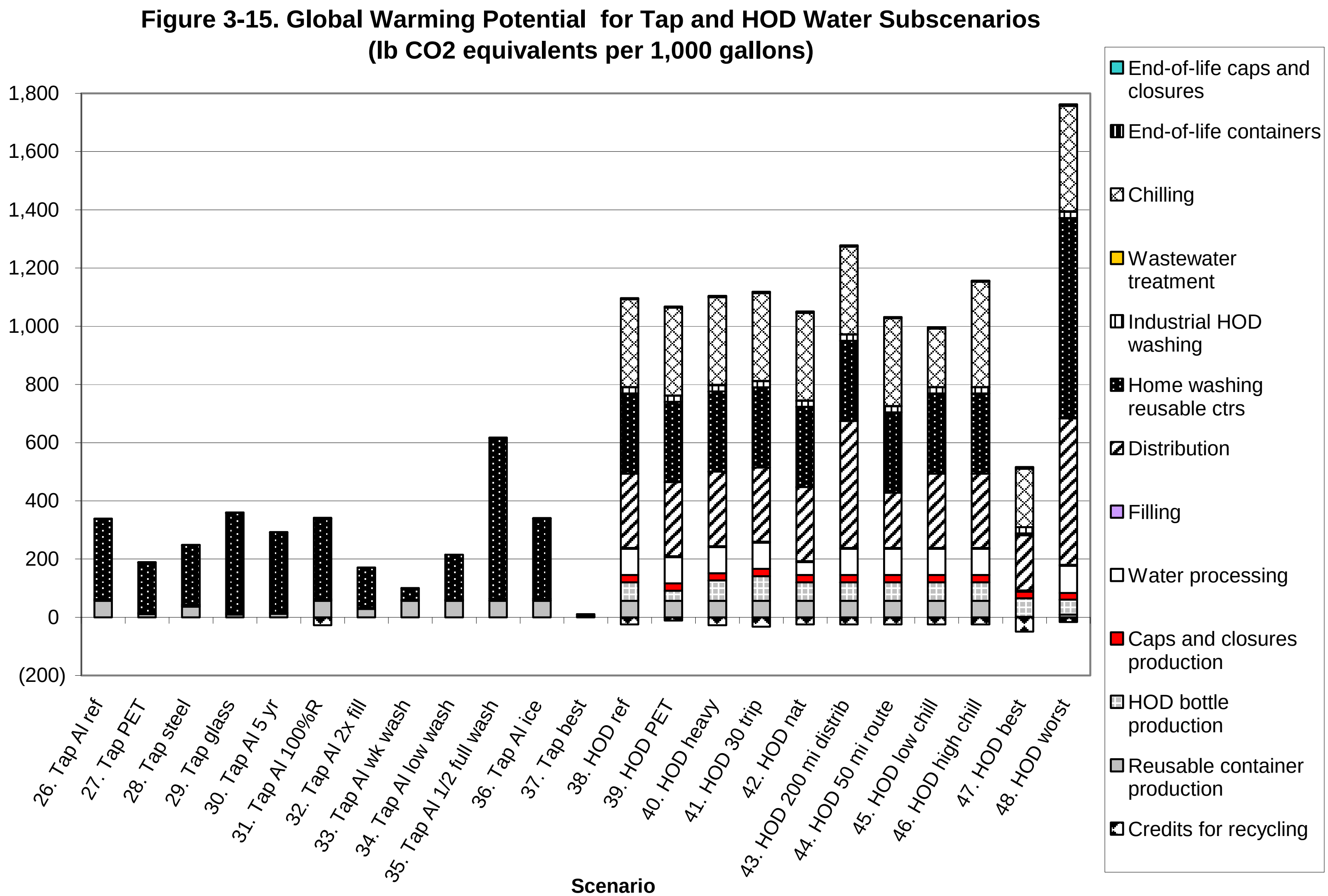
Figure 3-15. Global Warming Potential for Tap and HOD Water Subscenarios
(lb CO2 equivalents per 1,000 gallons)
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
(200)
26. Tap Al ref
27. Tap PET
28. Tap steel
29. Tap glass
30. Tap Al 5 yr
31. Tap Al 100%R
32. Tap Al 2x fill
33. Tap Al wk wash
34. Tap Al low wash
35. Tap Al 1/2 full wash
36. Tap Al ice
37. Tap best
38. HOD ref
39. HOD PET
40. HOD heavy
41. HOD 30 trip
42. HOD nat
43. HOD 200 mi distrib
44. HOD 50 mi route
45. HOD low chill
46. HOD high chill
47. HOD best
48. HOD worst
Scenario
End-of-life caps and closures
End-of-life containers
Chilling
Wastewater treatment
Industrial HOD washing
Home washing reusable ctrs
Distribution
Filling
Water processing
Caps and closures production
HOD bottle production
Reusable container production
Credits for recycling

Table 3-6. Water Use and Global Warming Potential: Possible Contribution of Carbon Dioxide from Groundwater* (page 1 of 2)
(gallons of water and lb CO2 equivalents per 1,000 gallons)

	Bottled Water												
	PET ref R1	PET ref R2	PET ref R3	PET 1 liter	PET 8 oz	PET light	PET light, low mold	25% rPET R1	25% rPET R2	25% rPET R3	PLA 0 decomp	PLA 100 decomp	PLA compost
	1	2	3	4	5	6	7	8	9	10	11	12	13
Bottled Water Scenarios													
Total life cycle GWP (see Table 3-6)	1,121	1,236	982	1,347	2,064	926	915	1,080	1,119	982	865	1,811	1253
Gallons water used as drinking water	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Percent groundwater	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Additional gallons lost during processing	250	250	250	250	250	250	250	250	250	250	250	250	250
Percent groundwater	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Total gallons water	1,250	1,250	1,250	1,250	1,250	1,250	1,250	1,250	1,250	1,250	1,250	1,250	1,250
Total gallons groundwater	0	0	0	0	0	0	0	0	0	0	0	0	0
Potential added CO2 from groundwater													
at 8.5 lb/1000 gal groundwater	0	0	0	0	0	0	0	0	0	0	0	0	0
at 85 lb/1000 gal groundwater	0	0	0	0	0	0	0	0	0	0	0	0	0
% Increase in GWP with groundwater CO2													
at 8.5 lb/1000 gal groundwater	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
at 85 lb/1000 gal groundwater	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

	Bottled Water											
	PET nat	PET Maine nat	PET Fiji nat	PET Fiji free sea	Glass France	PET 500 mi empty	PET 100% store trip	PET refrig	PET 37%R	PET best	PET worst	PLA best
	14	15	16	17	18	19	20	21	22	23	24	25
Bottled Water Scenarios												
Total life cycle GWP (see Table 3-6)	1,171	5,023	4,279	3,040	11,302	1,257	2,985	1,170	1,171	483	10,709	491
Gallons water used as drinking water	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Percent groundwater	100%	100%	100%	100%	100%	0%	0%	0%	0%	100%	100%	100%
Additional gallons lost during processing	0	0	0	0	0	250	250	250	250	0	0	0
Percent groundwater	100%	100%	100%	100%	100%	0%	0%	0%	0%	100%	100%	100%
Total gallons water	1,000	1,000	1,000	1,000	1,000	1,250	1,250	1,250	1,250	1,000	1,000	1,000
Total gallons groundwater	1,000	1,000	1,000	1,000	1,000	0	0	0	0	1,000	1,000	1,000
Potential added CO2 from groundwater												
at 8.5 lb/1000 gal groundwater	8.50	8.50	8.50	8.50	8.50	0	0	0	0	8.50	8.50	8.50
at 85 lb/1000 gal groundwater	85.0	85.0	85.0	85.0	85.0	0	0	0	0	85.0	85.0	85.0
% Increase in GWP with groundwater CO2												
at 8.5 lb/1000 gal groundwater	1%	0%	0%	0%	0%	0%	0%	0%	0%	2%	0%	2%
at 85 lb/1000 gal groundwater	7%	2%	2%	3%	1%	0%	0%	0%	0%	18%	1%	17%

Table 3-6. Water Use and Global Warming Potential: Possible Contribution of Carbon Dioxide from Groundwater* (page 2 of 2)
(gallons of water and lb CO2 equivalents per 1,000 gallons)

	Tap											
	Tap Al ref	Tap PET	Tap steel	Tap glass	Tap Al 5 yr	Tap Al 100%R	Tap Al 2x fill	Tap Al wk wash	Tap Al low wash	Tap Al 1/2 full wash	Tap Al ice	Tap best
	26	27	28	29	30	31	32	33	34	35	36	37
Tap Water Scenarios												
Total life cycle GWP (see Table 3-6)	339	189	249	360	293	315	171	101	215	618	340	10
Gallons water used as drinking water	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Percent groundwater	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Additional gallons lost during processing												
Percent groundwater												
Gallons water used for dishwashing	813	508	602	1,016	813	813	406	116	233	1,626	813	12.3
Percent groundwater	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Gallons water used for HOD washing												
Percent groundwater												
Total gallons water	1,813	1,508	1,602	2,016	1,813	1,813	1,406	1,116	1,233	2,626	1,813	1,012
Total gallons groundwater	453	377	401	504	453	453	352	279	308	656	453	253
Potential added CO2 from groundwater												
at 8.5 lb/1000 gal groundwater	3.85	3.20	3.40	4.28	3.85	3.85	2.99	2.37	2.62	5.58	3.85	2.15
at 85 lb/1000 gal groundwater	38.5	32.0	34.0	42.8	38.5	38.5	29.9	23.7	26.2	55.8	38.5	21.5
% Increase in GWP with groundwater CO2												
at 8.5 lb/1000 gal groundwater	1%	2%	1%	1%	1%	1%	2%	2%	1%	1%	1%	21%
at 85 lb/1000 gal groundwater	11%	17%	14%	12%	13%	12%	17%	24%	12%	9%	11%	205%

	HOD										
	HOD ref	HOD PET	HOD heavy	HOD 30 trip	HOD nat	HOD 200 mi distrib	HOD 50 mi route	HOD low chill	HOD high chill	HOD best	HOD worst
	38	39	40	41	42	43	44	45	46	47	48
HOD Water Scenarios											
Total life cycle GWP (see Table 3-6)	**1,072**	**1,057**	**1,077**	**1,086**	**1,026**	**1,253**	**1,007**	**972**	**1,132**	**467**	**1,746**
Gallons water used as drinking water	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Percent groundwater	0%	0%	0%	0%	100%	0%	0%	0%	0%	100%	0%
Additional gallons lost during processing	250	250	250	250	0	250	250	250	250	0	250
Percent groundwater	0%	0%	0%	0%	100%	0%	0%	0%	0%	100%	0%
Gallons water used for dishwashing	813	813	813	813	813	813	813	813	813	12.3	2,032
Percent groundwater	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Gallons water used for HOD washing	66	66	66	66	66	66	66	66	66	66	66
Percent groundwater	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Total gallons water	2,129	2,129	2,129	2,129	1,879	2,129	2,129	2,129	2,129	1,078	3,348
Total gallons groundwater	203	203	203	203	1,203	203	203	203	203	1,003	508
Potential added CO2 from groundwater											
at 8.5 lb/1000 gal groundwater	1.73	1.73	1.73	1.73	10.2	1.73	1.73	1.73	1.73	8.53	4.32
at 85 lb/1000 gal groundwater	17.3	17.3	17.3	17.3	102	17.3	17.3	17.3	17.3	85.3	43.2
% Increase in GWP with groundwater CO2											
at 8.5 lb/1000 gal groundwater	0%	0%	0%	0%	1%	0%	0%	0%	0%	2%	0%
at 85 lb/1000 gal groundwater	2%	2%	2%	2%	10%	1%	2%	2%	2%	18%	2%

* Based on range of estimates of dissolved carbon dioxide in groundwater (see Table E-3 of the Appendices). Spring water is modeled as 100% groundwater. As described in Appendix E, 25% of Oregon households get their water from wells, so Oregon tap water used for drinking and dishwashing is modeled as 25% groundwater. All other water from municipal water supplies is modeled as surface water.
NOTE: The water use data in this table includes water use and losses for delivery of drinking water and washing of containers. It does not include water use for the production of water containers and packaging materials. Water use for irrigation of corn used as an input to PLA production could account for significant quantities of groundwater (and associated dissolved CO2), depending on how much water is required for irrigation and whether the water is sourced from groundwater or surface water. Water losses during processing of municipal water are based on 25 percent losses for reverse osmosis.

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Table 3-7. Non-carcinogenic Potential by Life Cycle Stage for Drinking Water System Scenarios (page 1 of 2)
(lb toluene equivalents per 1,000 gallons)

	Bottled Water												
	PET ref R1	PET ref R2	PET ref R3	PET 1 liter	PET 8 oz	PET light	PET light, low mold	25% rPET R1	25% rPET R2	25% rPET R3	PLA 0 decomp	PLA 100 decomp	PLA compost
Bottled Water Scenarios	1	2	3	4	5	6	7	8	9	10	11	12	13
Production													
Disposable bottle	22,715	22,715	22,715	33,390	44,378	16,738	16,054	21,695	20,675	22,715	26,356	26,356	26,356
Caps and closures	3,120	3,120	3,120	2,730	5,768	2,730	2,730	3,120	3,120	3,120	3,120	3,120	3,120
Secondary packaging	75,731	75,731	75,731	37,865	159,982	75,731	75,731	75,731	75,731	75,731	75,731	75,731	75,731
Processes													
Water processing	5,354	5,354	5,354	5,354	5,354	5,354	5,354	5,354	5,354	5,354	5,354	5,354	5,354
Filling	207	207	207	207	207	207	207	207	207	207	207	207	207
Distribution	567	567	567	572	587	563	563	567	567	567	568	568	568
Consumer transport	708	708	708	356	1,490	708	708	708	708	708	708	708	708
Wastewater treatment	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9
Chilling	0	0	0	0	0	0	0	0	0	0	0	0	0
End of life management													
Containers	1,452	-151	3,301	2,135	2,837	1,070	1,070	1,487	-151	3,301	-300	-4,415	-330
Caps and closures	-93.1	-93.1	-93.1	-81.4	-172	-81.4	-81.4	-93.1	-93.1	-93.1	-93.1	-93.1	-93.1
Secondary packaging	-232	-155	-142	-116	-490	-232	-232	-232	-155	-142	-232	-232	-232
Credits for recycling	-29,239	0	-58,453	-15,389	-61,642	-29,030	-29,030	-29,140	0	-58,453	-28,446	-28,446	-28,446
TOTAL	**80,307**	**108,020**	**53,033**	**67,040**	**158,315**	**73,773**	**73,090**	**79,421**	**105,980**	**53,033**	**82,989**	**78,874**	**82,959**

	Bottled Water											
	PET nat	PET Maine nat	PET Fiji nat	PET Fiji free sea	Glass France	PET 500 mi empty	PET 100% store trip	PET refrig	PET 37%R	PET best	PET worst	PLA best
Bottled Water Scenarios	14	15	16	17	18	19	20	21	22	23	24	25
Production												
Disposable bottle	22,715	22,973	47,501	47,501	72,881	24,001	22,715	22,715	22,715	16,054	46,168	18,742
Caps and closures	3,120	3,120	5,071	5,071	36,774	3,120	3,120	3,120	3,120	2,730	5,768	2,730
Secondary packaging	75,731	75,731	75,731	75,731	105,773	75,731	75,731	75,731	75,731	1,200	175,099	1,200
Processes												
Water processing	2,563	2,634	3.94	3.94	3,550	5,354	5,354	5,354	5,354	3.83	2,928	3.83
Filling	207	213	213	213	287	207	207	207	207	207	213	207
Distribution	1,475	37,091	21,663	10,772	72,329	567	567	567	567	225	38,417	225
Consumer transport	708	708	708	708	990	708	17,576	708	708	4.75	37,124	4.75
Wastewater treatment	0	0	0	0	0	15.9	15.9	15.9	15.9	0	0.64	0
Chilling	0	0	0	0	0	0	0	2,991	0	0	12,636	0
End of life management												
Containers	1,452	1,452	3,003	3,003	6,301	1,452	1,452	1,452	707	4,103	-775	-221
Caps and closures	-93.1	-93.1	-151	-151	-1,097	-93.1	-93.1	-93.1	-93.1	-81.4	-172	-81.4
Secondary packaging	-232	-232	-232	-232	-324	-232	-232	-232	-232	-106	-536	-106
Credits for recycling	-29,239	-29,239	-30,086	-30,086	-61,425	-29,239	-29,239	-29,239	-28,919	-1,854	-65,773	0
TOTAL	**78,407**	**114,358**	**123,424**	**112,533**	**236,038**	**81,593**	**97,175**	**83,298**	**79,881**	**22,485**	**251,096**	**22,704**

Table 3-7. Non-carcinogenic Potential by Life Cycle Stage for Drinking Water System Scenarios (page 2 of 2)
(lb toluene equivalents per 1,000 gallons)

	Tap											
Tap Water Scenarios	Tap Al ref 26	Tap PET 27	Tap steel 28	Tap glass 29	Tap Al 5 yr 30	Tap Al 100%R 31	Tap Al 2x fill 32	Tap Al wk wash 33	Tap Al low wash 34	Tap Al 1/2 full wash 35	Tap Al ice 36	Tap best 37
Production												
Reusable drinking container	9,191	308	156	123	1,838	9,191	4,596	9,191	9,191	9,191	9,191	30.8
Caps and closures	56.4	50.7	123	0	11.3	56.4	28.2	56.4	56.4	56.4	56.4	5.07
Processes												
Water processing	246	204	217	273	246	246	190	151	167	356	313	137
Home washing of reusable container	14,295	8,934	10,589	17,869	14,295	14,295	7,148	2,042	8,643	28,590	14,295	386
Wastewater treatment	51.8	32.4	38.4	64.8	51.8	51.8	25.9	7.41	14.9	104	51.8	0.66
Chilling	0	0	0	0	0	0	0	0	0	0	0	0
End of life management												
Containers	2.15	-4.49	2.77	1.82	0.43	56.0	1.07	2.15	2.15	2.15	2.15	-0.45
Caps and closures	-1.68	-1.51	-3.68	0	-0.34	-1.68	-0.84	-1.68	-1.68	-1.68	-1.68	-0.15
Credits for recycling	0	0	0	0	0	-1,138	0	0	0	0	0	0
TOTAL	**23,840**	**9,524**	**11,123**	**18,332**	**16,442**	**22,756**	**11,988**	**11,449**	**18,073**	**38,297**	**23,908**	**559**

	HOD										
HOD Water Scenarios	HOD ref 38	HOD PET 39	HOD heavy 40	HOD 30 trip 41	HOD nat 42	HOD 200 mi distrib 43	HOD 50 mi route 44	HOD low chill 45	HOD high chill 46	HOD best 47	HOD worst 48
Production											
Reusable drinking container	9,191	9,191	9,191	9,191	9,191	9,191	9,191	9,191	9,191	30.8	123
HOD bottle	1,214	1,013	1,336	1,619	1,214	1,214	1,214	1,214	1,214	1,214	1,485
Caps and closures	729	729	729	729	729	729	729	729	729	678	673
Processes											
Water processing	5,473	5,473	5,473	5,473	2,681	5,473	5,473	5,473	5,473	13.7	5,638
Filling	207	207	207	207	207	207	207	207	207	207	207
Distribution	2,400	2,400	2,409	2,400	2,400	4,109	1,790	2,400	2,400	1,790	4,737
Home washing of reusable container	14,295	14,295	14,295	14,295	14,295	14,295	14,295	14,295	14,295	386	35,738
Industrial HOD washing	1,215	1,215	1,215	1,215	1,215	1,215	1,215	1,215	1,215	1,215	1,215
Wastewater treatment	72.0	72.0	72.0	72.0	56.0	72.0	72.0	72.0	72.0	4.87	150
Chilling	18,383	18,383	18,383	18,383	18,383	18,383	18,383	12,255	22,060	12,255	22,060
End of life management											
Containers	78.8	84.5	86.5	104	78.8	78.8	78.8	78.8	78.8	179	123
Caps and closures	-23.2	-23.2	-23.2	-23.2	-23.2	-23.2	-23.2	-23.2	-23.2	-21.6	-21.5
Credits for recycling	-292	-247	-322	-390	-292	-292	-292	-292	-292	-585	-362
TOTAL	**52,943**	**52,792**	**53,052**	**53,276**	**50,135**	**54,652**	**52,333**	**46,815**	**56,620**	**17,367**	**71,764**

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Figure 3-16. Non-carcinogenic Potential for Bottled Water Subscenarios (lb toluene equivalents per 1,000 gallons)

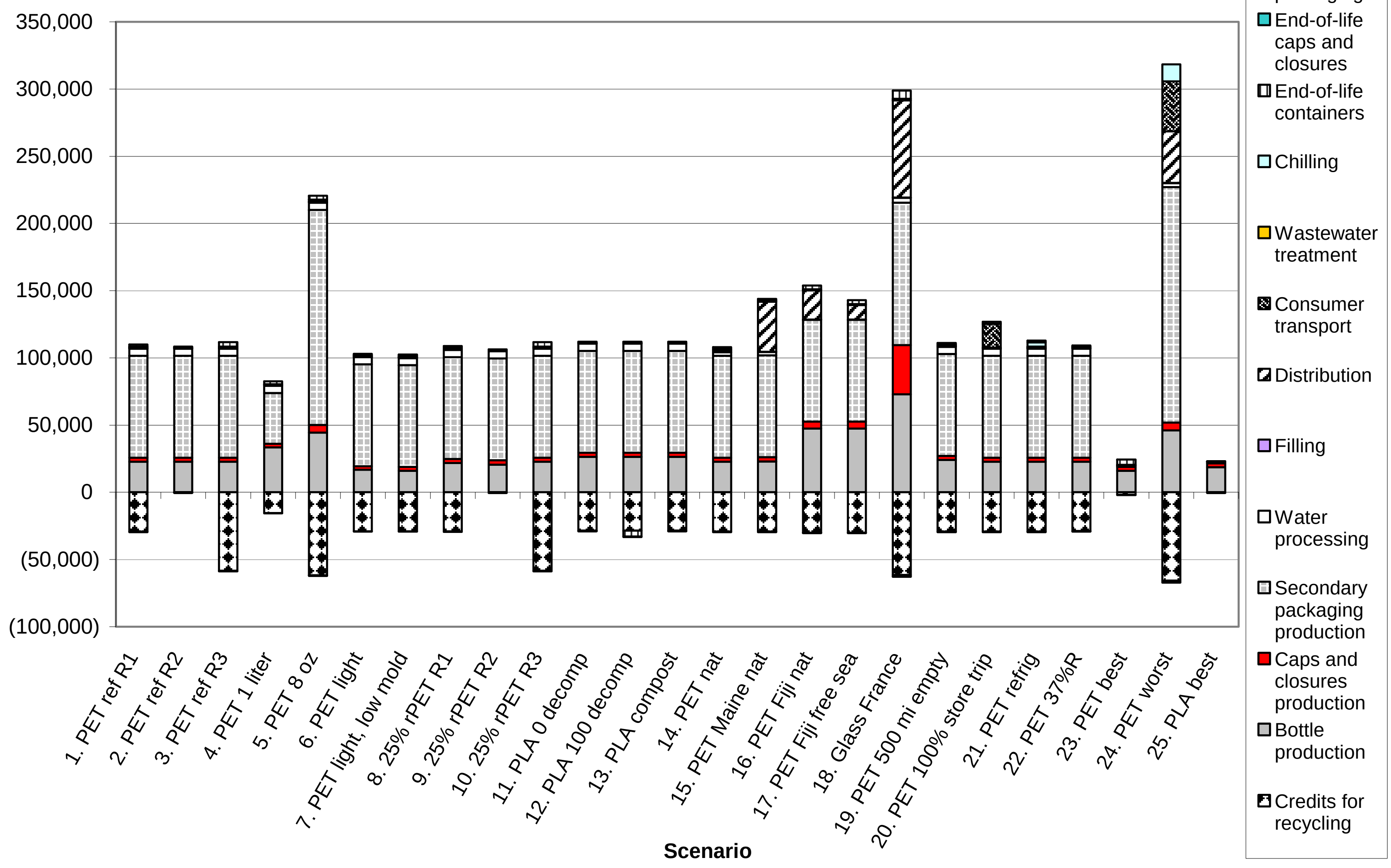

Figure 3-17. Non-carcinogenic Potential for Bottled Water Subscenarios excluding long-distance transport scenarios (lb toluene equivalents per 1,000 gallons)

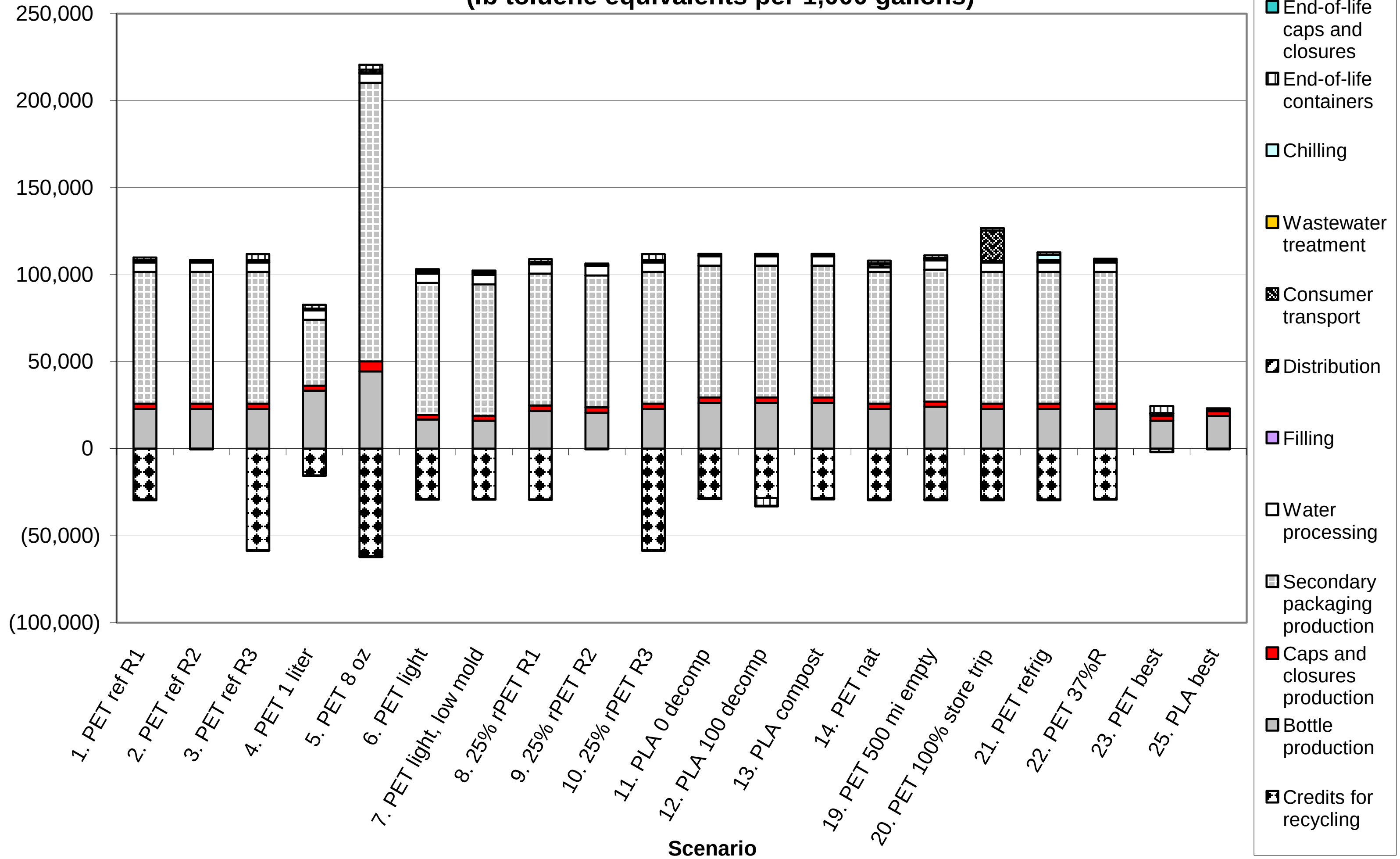

Figure 3-18. Non-carcinogenic Potential for Tap and HOD Water Subscenarios (lb toluene equivalents per 1,000 gallons)

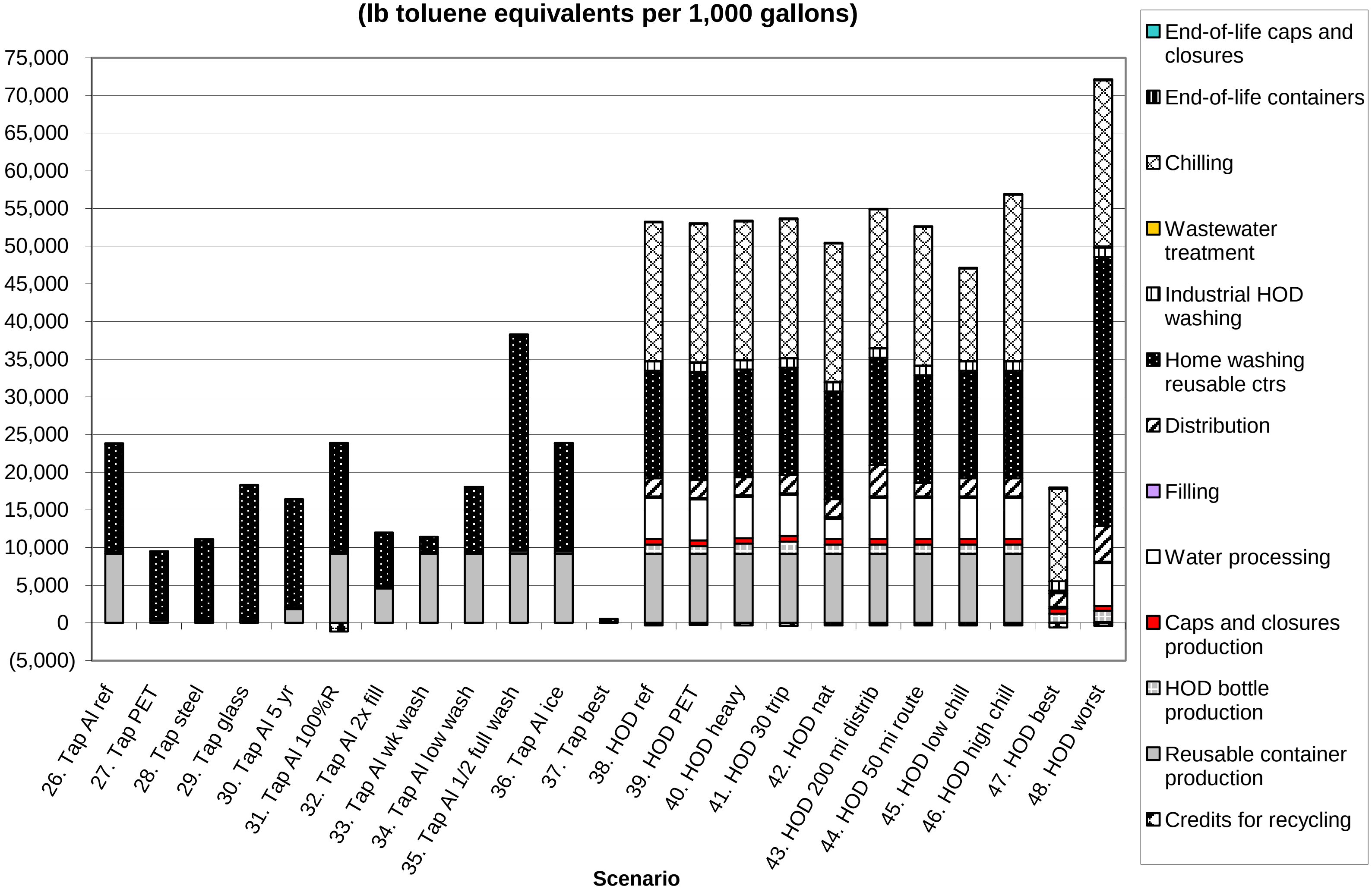

Table 3-8. Ozone Depletion Potential by Life Cycle Stage for Drinking Water System Scenarios (page 1 of 2)
(lb CFC-11 equivalents per 1,000 gallons)

	Bottled Water												
	PET ref R1	PET ref R2	PET ref R3	PET 1 liter	PET 8 oz	PET light	PET light, low mold	25% rPET R1	25% rPET R2	25% rPET R3	PLA 0 decomp	PLA 100 decomp	PLA compost
Bottled Water Scenarios	1	2	3	4	5	6	7	8	9	10	11	12	13
Production													
Disposable bottle	1.2E-06	1.2E-06	1.2E-06	1.7E-06	2.3E-06	8.7E-07	8.3E-07	1.1E-06	1.1E-06	1.2E-06	1.4E-06	1.4E-06	1.4E-06
Caps and closures	1.3E-07	1.3E-07	1.3E-07	1.2E-07	2.5E-07	1.2E-07	1.2E-07	1.3E-07	1.3E-07	1.3E-07	1.3E-07	1.3E-07	1.3E-07
Secondary packaging	5.7E-06	5.7E-06	5.7E-06	2.9E-06	1.2E-05	5.7E-06	5.7E-06	5.7E-06	5.7E-06	5.7E-06	5.7E-06	5.7E-06	5.7E-06
Processes													
Water processing	3.1E-07	3.1E-07	3.1E-07	3.1E-07	3.1E-07	3.1E-07	3.1E-07	3.1E-07	3.1E-07	3.1E-07	3.1E-07	3.1E-07	3.1E-07
Filling	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08
Distribution	9.6E-09	9.6E-09	9.6E-09	9.7E-09	1.0E-08	9.6E-09	9.6E-09	9.6E-09	9.6E-09	9.6E-09	9.6E-09	9.6E-09	9.6E-09
Consumer transport	1.2E-08	1.2E-08	1.2E-08	6.0E-09	2.5E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08
Wastewater treatment	1.2E-09	1.2E-09	1.2E-09	1.2E-09	1.2E-09	1.2E-09	1.2E-09	1.2E-09	1.2E-09	1.2E-09	1.2E-09	1.2E-09	1.2E-09
Chilling	0	0	0	0	0	0	0	0	0	0	0	0	0
End of life management													
Containers	6.7E-08	-1.1E-08	1.6E-07	9.8E-08	1.3E-07	4.9E-08	4.9E-08	6.9E-08	-1.1E-08	1.6E-07	-2.3E-08	-2.5E-07	-2.3E-08
Caps and closures	-5.9E-09	-5.9E-09	-5.9E-09	-5.1E-09	-1.1E-08	-5.1E-09	-5.1E-09	-5.9E-09	-5.9E-09	-5.9E-09	-5.9E-09	-5.9E-09	-5.9E-09
Secondary packaging	-1.4E-08	-9.1E-09	-8.8E-09	-6.9E-09	-2.9E-08	-1.4E-08	-1.4E-08	-1.4E-08	-9.1E-09	-8.8E-09	-1.4E-08	-1.4E-08	-1.4E-08
Credits for recycling	-1.8E-06	0	-3.6E-06	-9.8E-07	-3.8E-06	-1.8E-06	-1.8E-06	-1.8E-06	0	-3.6E-06	-1.7E-06	-1.7E-06	-1.7E-06
TOTAL	**5.6E-06**	**7.3E-06**	**3.9E-06**	**4.1E-06**	**1.1E-05**	**5.3E-06**	**5.3E-06**	**5.6E-06**	**7.2E-06**	**3.9E-06**	**5.8E-06**	**5.6E-06**	**5.8E-06**

	Bottled Water											
	PET nat	PET Maine nat	PET Fiji nat	PET Fiji free sea	Glass France	PET 500 mi empty	PET 100% store trip	PET refrig	PET 37%R	PET best	PET worst	PLA best
Bottled Water Scenarios	14	15	16	17	18	19	20	21	22	23	24	25
Production												
Disposable bottle	1.2E-06	1.2E-06	2.4E-06	2.4E-06	5.6E-06	1.2E-06	1.2E-06	1.2E-06	1.2E-06	8.3E-07	2.3E-06	9.7E-07
Caps and closures	1.3E-07	1.3E-07	2.2E-07	2.2E-07	1.6E-06	1.3E-07	1.3E-07	1.3E-07	1.3E-07	1.2E-07	2.5E-07	1.2E-07
Secondary packaging	5.7E-06	5.7E-06	5.7E-06	5.7E-06	8.0E-06	5.7E-06	5.7E-06	5.7E-06	5.7E-06	1.3E-06	1.3E-05	1.3E-06
Processes												
Water processing	1.4E-07	1.4E-07	2.2E-10	2.2E-10	2.0E-07	3.1E-07	3.1E-07	3.1E-07	3.1E-07	2.1E-10	1.6E-07	2.1E-10
Filling	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.6E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08
Distribution	2.5E-08	6.3E-07	3.7E-07	1.8E-07	1.4E-06	9.6E-09	9.6E-09	9.6E-09	9.6E-09	3.8E-09	6.5E-07	3.8E-09
Consumer transport	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.7E-08	1.2E-08	3.0E-07	1.2E-08	1.2E-08	8.0E-11	6.3E-07	8.1E-11
Wastewater treatment	0	0	0	0	0	1.2E-09	1.2E-09	1.2E-09	1.2E-09	0	4.7E-11	0
Chilling	0	0	0	0	0	0	0	1.7E-07	0	0	7.0E-07	0
End of life management												
Containers	6.7E-08	6.7E-08	1.4E-07	1.4E-07	3.1E-07	6.7E-08	6.7E-08	6.7E-08	2.9E-08	2.0E-07	-5.4E-08	-1.7E-08
Caps and closures	-5.9E-09	-5.9E-09	-9.5E-09	-9.5E-09	-6.9E-08	-5.9E-09	-5.9E-09	-5.9E-09	-5.9E-09	-5.1E-09	-1.1E-08	-5.1E-09
Secondary packaging	-1.4E-08	-1.4E-08	-1.4E-08	-1.4E-08	-1.9E-08	-1.4E-08	-1.4E-08	-1.4E-08	-1.4E-08	-6.3E-09	-3.2E-08	-6.3E-09
Credits for recycling	-1.8E-06	-1.8E-06	-1.9E-06	-1.9E-06	-4.2E-06	-1.8E-06	-1.8E-06	-1.8E-06	-1.8E-06	-2.0E-07	-4.0E-06	0
TOTAL	**5.5E-06**	**6.1E-06**	**7.0E-06**	**6.8E-06**	**1.3E-05**	**5.6E-06**	**5.9E-06**	**5.8E-06**	**5.6E-06**	**2.2E-06**	**1.4E-05**	**2.3E-06**

Table 3-8. Ozone Depletion Potential by Life Cycle Stage for Drinking Water System Scenarios (page 2 of 2)
(lb CFC-11 equivalents per 1,000 gallons)

	Tap											
	Tap Al ref	Tap PET	Tap steel	Tap glass	Tap Al 5 yr	Tap Al 100%R	Tap Al 2x fill	Tap Al wk wash	Tap Al low wash	Tap Al 1/2 full wash	Tap Al ice	Tap best
Tap Water Scenarios	26	27	28	29	30	31	32	33	34	35	36	37
Production												
Reusable drinking container	5.2E-07	1.6E-08	3.0E-09	1.0E-08	1.0E-07	5.2E-07	2.6E-07	5.2E-07	5.2E-07	5.2E-07	5.2E-07	1.6E-09
Caps and closures	2.4E-09	2.2E-09	5.2E-09	0	4.8E-10	2.4E-09	1.2E-09	2.4E-09	2.4E-09	2.4E-09	2.4E-09	2.2E-10
Processes												
Water processing	2.7E-08	2.2E-08	2.4E-08	3.0E-08	2.7E-08	2.7E-08	2.1E-08	1.6E-08	1.8E-08	3.9E-08	3.4E-08	1.5E-08
Home washing of reusable container	7.8E-07	4.9E-07	5.8E-07	9.8E-07	7.8E-07	7.8E-07	3.9E-07	1.1E-07	4.8E-07	1.6E-06	7.8E-07	2.1E-08
Wastewater treatment	3.8E-09	2.4E-09	2.8E-09	4.8E-09	3.8E-09	3.8E-09	1.9E-09	5.5E-10	1.1E-09	7.7E-09	3.8E-09	4.9E-11
Chilling	0	0	0	0	0	0	0	0	0	0	0	0
End of life management												
Containers	3.6E-11	-3.1E-10	4.6E-11	3.1E-11	7.1E-12	2.6E-09	1.8E-11	3.6E-11	3.6E-11	3.6E-11	3.6E-11	-3.1E-11
Caps and closures	-1.1E-10	-9.5E-11	-2.3E-10	0	-2.1E-11	-1.1E-10	-5.3E-11	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10	-9.5E-12
Credits for recycling	0	0	0	0	0	-6.3E-08	0	0	0	0	0	0
TOTAL	**1.3E-06**	**5.3E-07**	**6.2E-07**	**1.0E-06**	**9.2E-07**	**1.3E-06**	**6.7E-07**	**6.5E-07**	**1.0E-06**	**2.1E-06**	**1.3E-06**	**3.8E-08**

	HOD										
	HOD ref	HOD PET	HOD heavy	HOD 30 trip	HOD nat	HOD 200 mi distrib	HOD 50 mi route	HOD low chill	HOD high chill	HOD best	HOD worst
HOD Water Scenarios	38	39	40	41	42	43	44	45	46	47	48
Production											
Reusable drinking container	5.2E-07	5.2E-07	5.2E-07	5.2E-07	5.2E-07	5.2E-07	5.2E-07	5.2E-07	5.2E-07	1.6E-09	1.0E-08
HOD bottle	1.4E-07	5.2E-08	1.6E-07	1.9E-07	1.4E-07	1.4E-07	1.4E-07	1.4E-07	1.4E-07	1.4E-07	7.7E-08
Caps and closures	3.4E-07	3.4E-07	3.4E-07	3.4E-07	3.4E-07	3.4E-07	3.4E-07	3.4E-07	3.4E-07	3.4E-07	3.4E-07
Processes											
Water processing	3.2E-07	3.2E-07	3.2E-07	3.2E-07	1.6E-07	3.2E-07	3.2E-07	3.2E-07	3.2E-07	1.5E-09	3.4E-07
Filling	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.2E-08
Distribution	4.1E-08	4.1E-08	4.1E-08	4.1E-08	4.1E-08	7.0E-08	3.0E-08	4.1E-08	4.1E-08	3.0E-08	8.0E-08
Home washing of reusable container	7.8E-07	7.8E-07	7.8E-07	7.8E-07	7.8E-07	7.8E-07	7.8E-07	7.8E-07	7.8E-07	2.1E-08	2.0E-06
Industrial HOD washing	6.8E-08	6.8E-08	6.8E-08	6.8E-08	6.8E-08	6.8E-08	6.8E-08	6.8E-08	6.8E-08	6.8E-08	6.8E-08
Wastewater treatment	5.3E-09	5.3E-09	5.3E-09	5.3E-09	4.1E-09	5.3E-09	5.3E-09	5.3E-09	5.3E-09	3.6E-10	1.1E-08
Chilling	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06	6.8E-07	1.2E-06	6.8E-07	1.2E-06
End of life management											
Containers	4.1E-09	4.4E-09	4.5E-09	5.5E-09	4.1E-09	4.1E-09	4.1E-09	4.1E-09	4.1E-09	9.8E-09	6.5E-09
Caps and closures	-1.5E-09	-1.5E-09	-1.5E-09	-1.5E-09	-1.5E-09	-1.5E-09	-1.5E-09	-1.5E-09	-1.5E-09	-1.4E-09	-1.4E-09
Credits for recycling	-5.5E-08	-1.2E-08	-6.0E-08	-7.3E-08	-5.5E-08	-5.5E-08	-5.5E-08	-5.5E-08	-5.5E-08	-1.1E-07	-1.8E-08
TOTAL	**3.2E-06**	**3.2E-06**	**3.2E-06**	**3.2E-06**	**3.0E-06**	**3.2E-06**	**3.2E-06**	**2.9E-06**	**3.4E-06**	**1.2E-06**	**4.1E-06**

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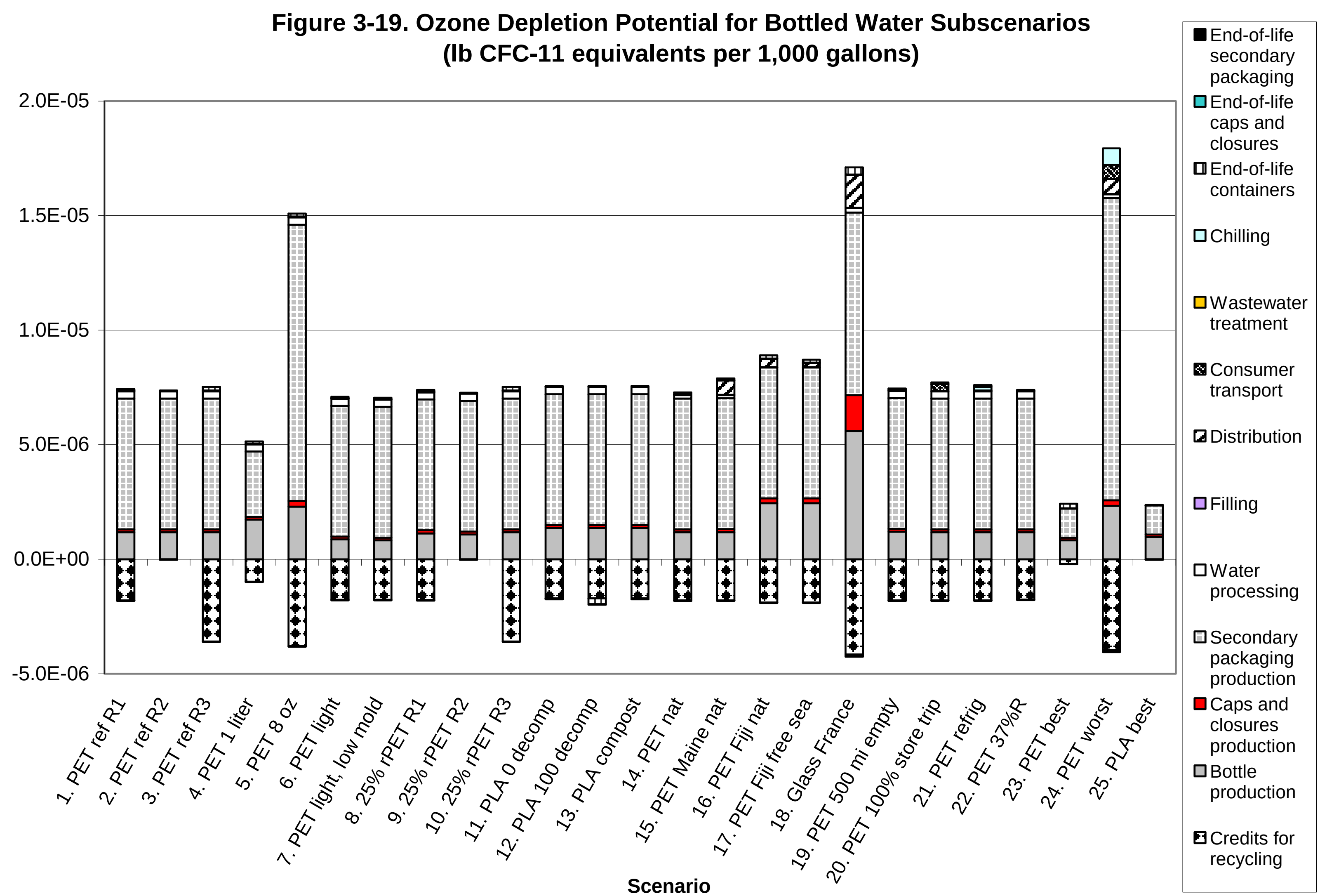

Figure 3-19. Ozone Depletion Potential for Bottled Water Subscenarios
(lb CFC-11 equivalents per 1,000 gallons)
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
-5.0E-06
1. PET ref R1
2. PET ref R2
3. PET ref R3
4. PET 1 liter
5. PET 8 oz
6. PET light
7. PET light, low mold
8. 25% rPET R1
9. 25% rPET R2
10. 25% rPET R3
11. PLA 0 decomp
12. PLA 100 decomp
13. PLA compost
14. PET nat
15. PET Maine nat
16. PET Fiji nat
17. PET Fiji free sea
18. Glass France
19. PET 500 mi empty
20. PET 100% store trip
21. PET refrig
22. PET 37%R
23. PET best
24. PET worst
25. PLA best
Scenario
End-of-life secondary packaging
End-of-life caps and closures
End-of-life containers
Chilling
Wastewater treatment
Consumer transport
Distribution
Filling
Water processing
Secondary packaging production
Caps and closures production
Bottle production
Credits for recycling

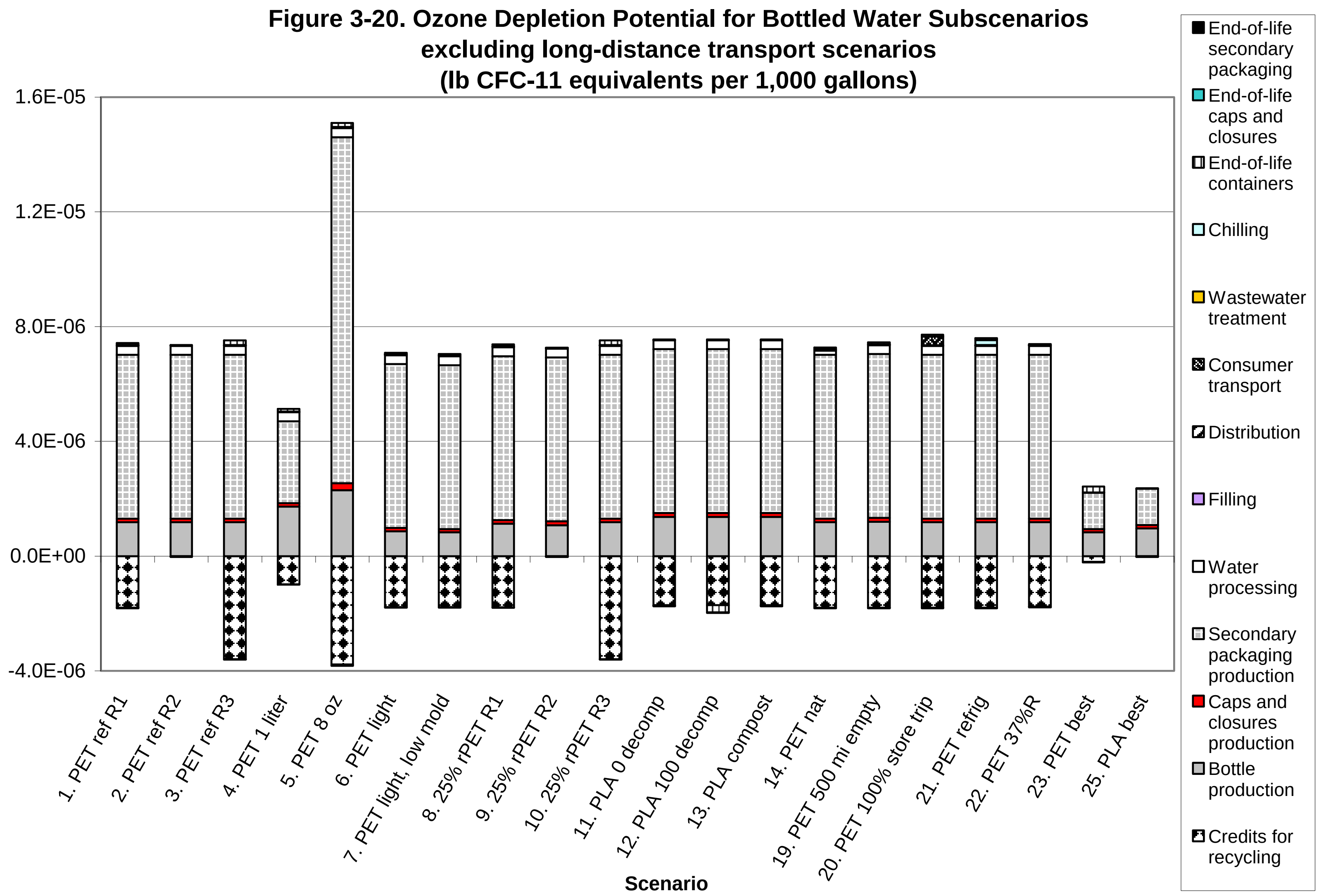
Figure 3-20. Ozone Depletion Potential for Bottled Water Subscenarios
excluding long-distance transport scenarios
(lb CFC-11 equivalents per 1,000 gallons)
1.6E-05
1.2E-05
8.0E-06
4.0E-06
0.0E+00
-4.0E-06
1. PET ref R1
2. PET ref R2
3. PET ref R3
4. PET 1 liter
5. PET 8 oz
6. PET light
7. PET light, low mold
8. 25% rPET R1
9. 25% rPET R2
10. 25% rPET R3
11. PLA 0 decomp
12. PLA 100 decomp
13. PLA compost
14. PET nat
19. PET 500 mi empty
20. PET 100% store trip
21. PET refrig
22. PET 37%R
23. PET best
25. PLA best
Scenario
End-of-life secondary packaging
End-of-life caps and closures
End-of-life containers
Chilling
Wastewater treatment
Consumer transport
Distribution
Filling
Water processing
Secondary packaging production
Caps and closures production
Bottle production
Credits for recycling

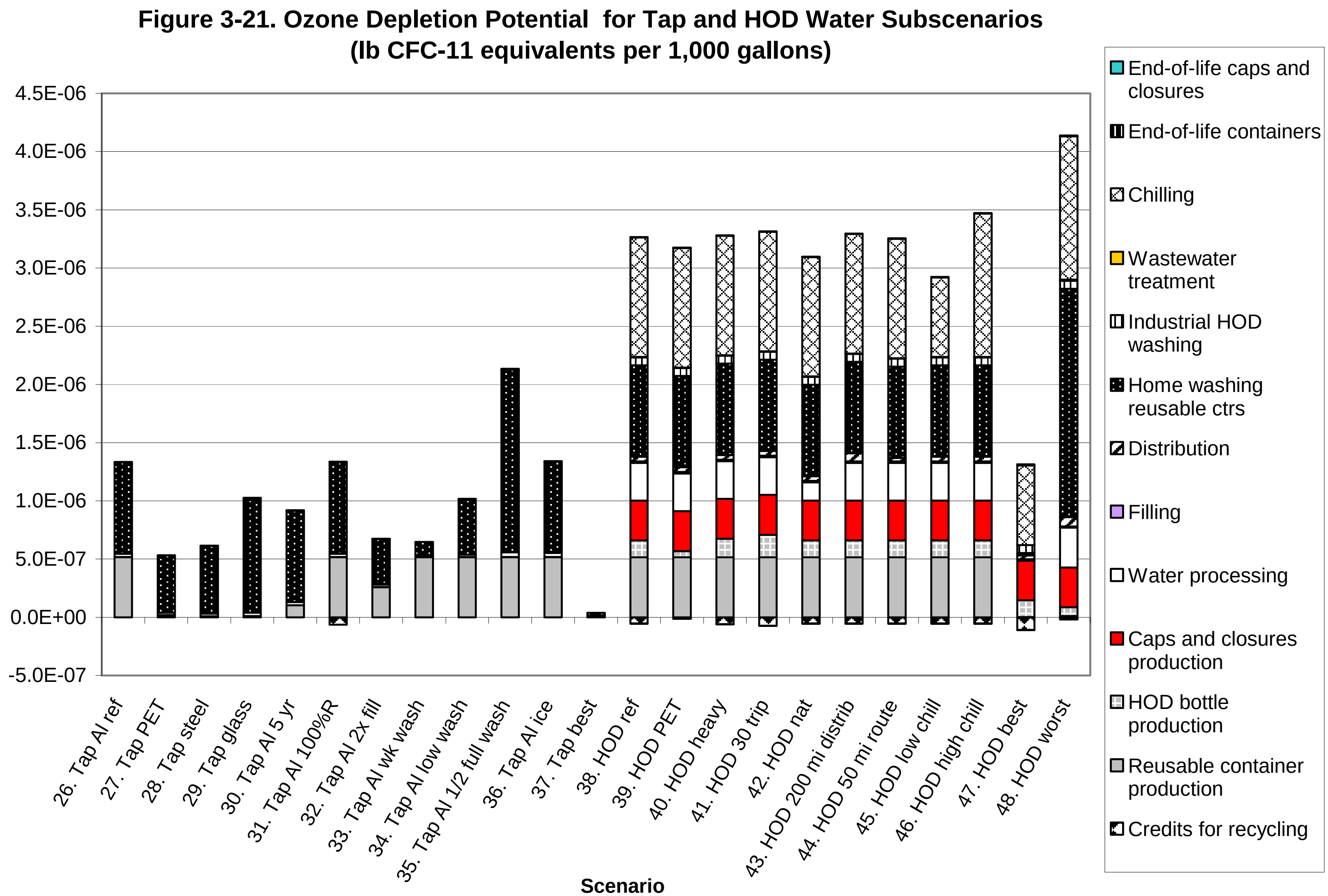
Figure 3-21. Ozone Depletion Potential for Tap and HOD Water Subscenarios
(lb CFC-11 equivalents per 1,000 gallons)
4.5E-06
4.0E-06
3.5E-06
3.0E-06
2.5E-06
2.0E-06
1.5E-06
1.0E-06
5.0E-07
0.0E+00
-5.0E-07
26. Tap Al ref
27. Tap PET
28. Tap steel
29. Tap glass
30. Tap Al 5 yr
31. Tap Al 100%R
32. Tap Al 2x fill
33. Tap Al wk wash
34. Tap Al low wash
35. Tap Al 1/2 full wash
36. Tap Al ice
37. Tap best
38. HOD ref
39. HOD PET
40. HOD heavy
41. HOD 30 trip
42. HOD nat
43. HOD 200 mi distrib
44. HOD 50 mi route
45. HOD low chill
46. HOD high chill
47. HOD best
48. HOD worst
Scenario
End-of-life caps and closures
End-of-life containers
Chilling
Wastewater treatment
Industrial HOD washing
Home washing reusable ctrs
Distribution
Filling
Water processing
Caps and closures production
HOD bottle production
Reusable container production
Credits for recycling

Table 3-9. Respiratory Effects Potential by Life Cycle Stage for Drinking Water System Scenarios (page 1 of 2)
(lb PM 2.5 equivalents per 1,000 gallons)

	Bottled Water												
	PET ref R1	PET ref R2	PET ref R3	PET 1 liter	PET 8 oz	PET light	PET light, low mold	25% rPET R1	25% rPET R2	25% rPET R3	PLA 0 decomp	PLA 100 decomp	PLA compost
Bottled Water Scenarios	1	2	3	4	5	6	7	8	9	10	11	12	13
Production													
Disposable bottle	1.29	1.29	1.29	1.89	2.52	0.95	0.93	1.20	1.11	1.29	1.78	1.78	1.78
Caps and closures	0.15	0.15	0.15	0.13	0.27	0.13	0.13	0.15	0.15	0.15	0.15	0.15	0.15
Secondary packaging	0.28	0.28	0.28	0.14	0.59	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Processes													
Water processing	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Filling	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071
Distribution	0.034	0.034	0.034	0.034	0.035	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034
Consumer transport	0.028	0.028	0.028	0.014	0.058	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
Wastewater treatment	6.3E-04	6.3E-04	6.3E-04	6.3E-04	6.3E-04	6.3E-04	6.3E-04	6.3E-04	6.3E-04	6.3E-04	6.3E-04	6.3E-04	6.3E-04
Chilling	0	0	0	0	0	0	0	0	0	0	0	0	0
End of life management													
Containers	0.10	-0.0034	0.21	0.15	0.20	0.074	0.074	0.10	-0.0034	0.21	-0.0055	-0.15	-0.0085
Caps and closures	-0.0026	-0.0026	-0.0026	-0.0023	-0.0049	-0.0023	-0.0023	-0.0026	-0.0026	-0.0026	-0.0026	-0.0026	-0.0026
Secondary packaging	-0.0073	-0.0050	-0.0042	-0.0037	-0.015	-0.0073	-0.0073	-0.0073	-0.0050	-0.0042	-0.0073	-0.0073	-0.0073
Credits for recycling	-0.38	0	-0.75	-0.49	-0.75	-0.30	-0.30	-0.34	0	-0.75	-0.073	-0.073	-0.073
TOTAL	**1.68**	**1.96**	**1.43**	**2.06**	**3.09**	**1.38**	**1.35**	**1.63**	**1.78**	**1.43**	**2.37**	**2.23**	**2.37**

	Bottled Water											
	PET nat	PET Maine nat	PET Fiji nat	PET Fiji free sea	Glass France	PET 500 mi empty	PET 100% store trip	PET refrig	PET 37%R	PET best	PET worst	PLA best
Bottled Water Scenarios	14	15	16	17	18	19	20	21	22	23	24	25
Production												
Disposable bottle	1.29	1.39	2.88	2.88	51.6	1.36	1.29	1.29	1.29	0.93	2.80	1.28
Caps and closures	0.15	0.15	0.24	0.24	1.74	0.15	0.15	0.15	0.15	0.13	0.27	0.13
Secondary packaging	0.28	0.28	0.28	0.28	0.39	0.28	0.28	0.28	0.28	0.090	0.64	0.090
Processes												
Water processing	0.088	0.12	1.8E-04	1.8E-04	0.075	0.19	0.19	0.19	0.19	1.3E-04	0.13	1.3E-04
Filling	0.0071	0.0095	0.0095	0.0095	0.0061	0.0071	0.0071	0.0071	0.0071	0.0071	0.0095	0.0071
Distribution	0.089	2.23	3.76	0.65	6.46	0.034	0.034	0.034	0.034	0.014	2.31	0.014
Consumer transport	0.028	0.028	0.028	0.028	0.039	0.028	0.69	0.028	0.028	1.9E-04	1.45	1.9E-04
Wastewater treatment	0	0	0	0	0	6.3E-04	6.3E-04	6.3E-04	6.3E-04	0	2.5E-05	0
Chilling	0	0	0	0	0	0	0	0.10	0	0	0.44	0
End of life management												
Containers	0.10	0.10	0.21	0.21	0.32	0.10	0.10	0.10	0.056	0.25	-0.018	-0.0040
Caps and closures	-0.0026	-0.0026	-0.0043	-0.0043	-0.031	-0.0026	-0.0026	-0.0026	-0.0026	-0.0023	-0.0049	-0.0023
Secondary packaging	-0.0073	-0.0073	-0.0073	-0.0073	-0.010	-0.0073	-0.0073	-0.0073	-0.0073	-0.0033	-0.017	-0.0033
Credits for recycling	-0.38	-0.38	-0.70	-0.70	-19.4	-0.38	-0.38	-0.38	-0.25	-0.71	-0.17	0
TOTAL	**1.64**	**3.92**	**6.69**	**3.58**	**41.1**	**1.76**	**2.34**	**1.78**	**1.76**	**0.70**	**7.85**	**1.51**

Table 3-9. Respiratory Effects Potential by Life Cycle Stage for Drinking Water System Scenarios (page 2 of 2)
(lb PM 2.5 equivalents per 1,000 gallons)

	Tap											
Tap Water Scenarios	Tap Al ref 26	Tap PET 27	Tap steel 28	Tap glass 29	Tap Al 5 yr 30	Tap Al 100%R 31	Tap Al 2x fill 32	Tap Al wk wash 33	Tap Al low wash 34	Tap Al 1/2 full wash 35	Tap Al ice 36	Tap best 37
Production												
Reusable drinking container	0.13	0.018	0.049	0.11	0.025	0.13	0.064	0.13	0.13	0.13	0.13	0.0018
Caps and closures	0.0027	0.0024	0.0058	0	5.3E-04	0.0027	0.0013	0.0027	0.0027	0.0027	0.0027	2.4E-04
Processes												
Water processing	0.0088	0.0073	0.0078	0.0098	0.0088	0.0088	0.0068	0.0054	0.0060	0.013	0.011	0.0049
Home washing of reusable container	0.58	0.36	0.43	0.72	0.58	0.58	0.29	0.082	0.32	1.15	0.58	0.014
Wastewater treatment	0.0020	0.0013	0.0015	0.0026	0.0020	0.0020	0.0010	2.9E-04	5.9E-04	0.0041	0.0020	2.6E-05
Chilling	0	0	0	0	0	0	0	0	0	0	0	0
End of life management												
Containers	1.6E-04	-1.0E-04	1.9E-04	1.2E-04	3.1E-05	0.0044	7.9E-05	1.6E-04	1.6E-04	1.6E-04	1.6E-04	-1.0E-05
Caps and closures	-4.8E-05	-4.3E-05	-1.0E-04	0	-9.6E-06	-4.8E-05	-2.4E-05	-4.8E-05	-4.8E-05	-4.8E-05	-4.8E-05	-4.3E-06
Credits for recycling	0	0	0	0	0	-0.060	0	0	0	0	0	0
TOTAL	**0.72**	**0.39**	**0.49**	**0.84**	**0.61**	**0.66**	**0.36**	**0.22**	**0.46**	**1.30**	**0.72**	**0.021**

	HOD										
HOD Water Scenarios	HOD ref 38	HOD PET 39	HOD heavy 40	HOD 30 trip 41	HOD nat 42	HOD 200 mi distrib 43	HOD 50 mi route 44	HOD low chill 45	HOD high chill 46	HOD best 47	HOD worst 48
Production											
Reusable drinking container	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.0018	0.11
HOD bottle	0.12	0.059	0.13	0.16	0.12	0.12	0.12	0.12	0.12	0.12	0.087
Caps and closures	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.040	0.039
Processes											
Water processing	0.19	0.19	0.19	0.19	0.093	0.19	0.19	0.19	0.19	4.9E-04	0.20
Filling	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071
Distribution	0.14	0.14	0.14	0.14	0.14	0.24	0.10	0.14	0.14	0.10	0.28
Home washing of reusable container	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.014	1.44
Industrial HOD washing	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044
Wastewater treatment	0.0028	0.0028	0.0028	0.0028	0.0022	0.0028	0.0028	0.0028	0.0028	1.9E-04	0.0059
Chilling	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.42	0.76	0.42	0.76
End of life management											
Containers	0.0038	0.0040	0.0042	0.0050	0.0038	0.0038	0.0038	0.0038	0.0038	0.0080	0.0058
Caps and closures	-6.6E-04	-6.6E-04	-6.6E-04	-6.6E-04	-6.6E-04	-6.6E-04	-6.6E-04	-6.6E-04	-6.6E-04	-6.1E-04	-6.1E-04
Credits for recycling	-0.045	-0.018	-0.049	-0.060	-0.045	-0.045	-0.045	-0.045	-0.045	-0.090	-0.026
TOTAL	**1.84**	**1.81**	**1.85**	**1.86**	**1.74**	**1.94**	**1.80**	**1.63**	**1.97**	**0.67**	**2.95**

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Figure 3-22. Respiratory Effects Potential for Bottled Water Subscenarios (lb PM 2.5 equivalents per 1,000 gallons)

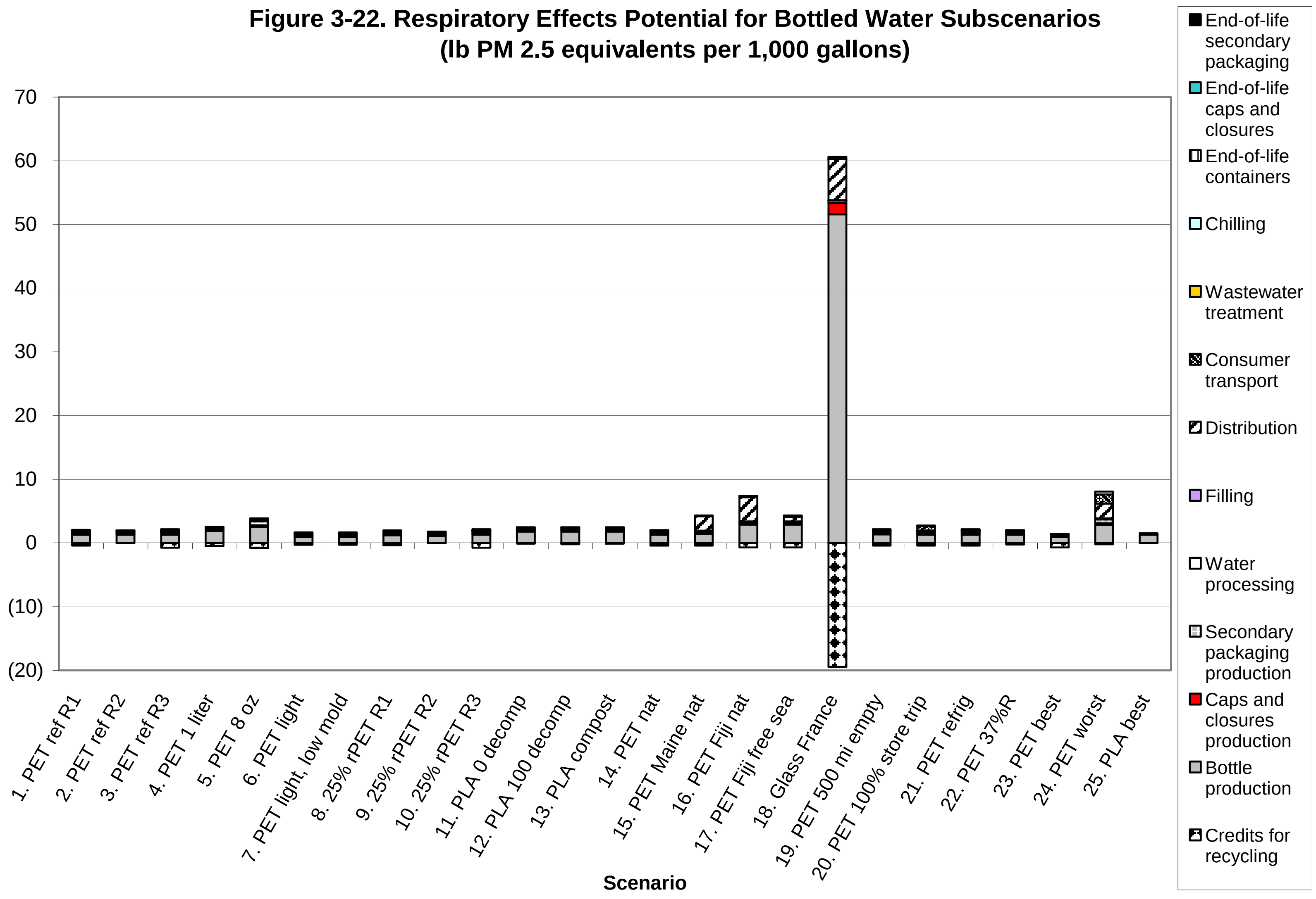

Figure 3-23. Respiratory Effects Potential for Bottled Water Subscenarios excluding long-distance transport scenarios (lb PM 2.5 equivalents per 1,000 gallons)

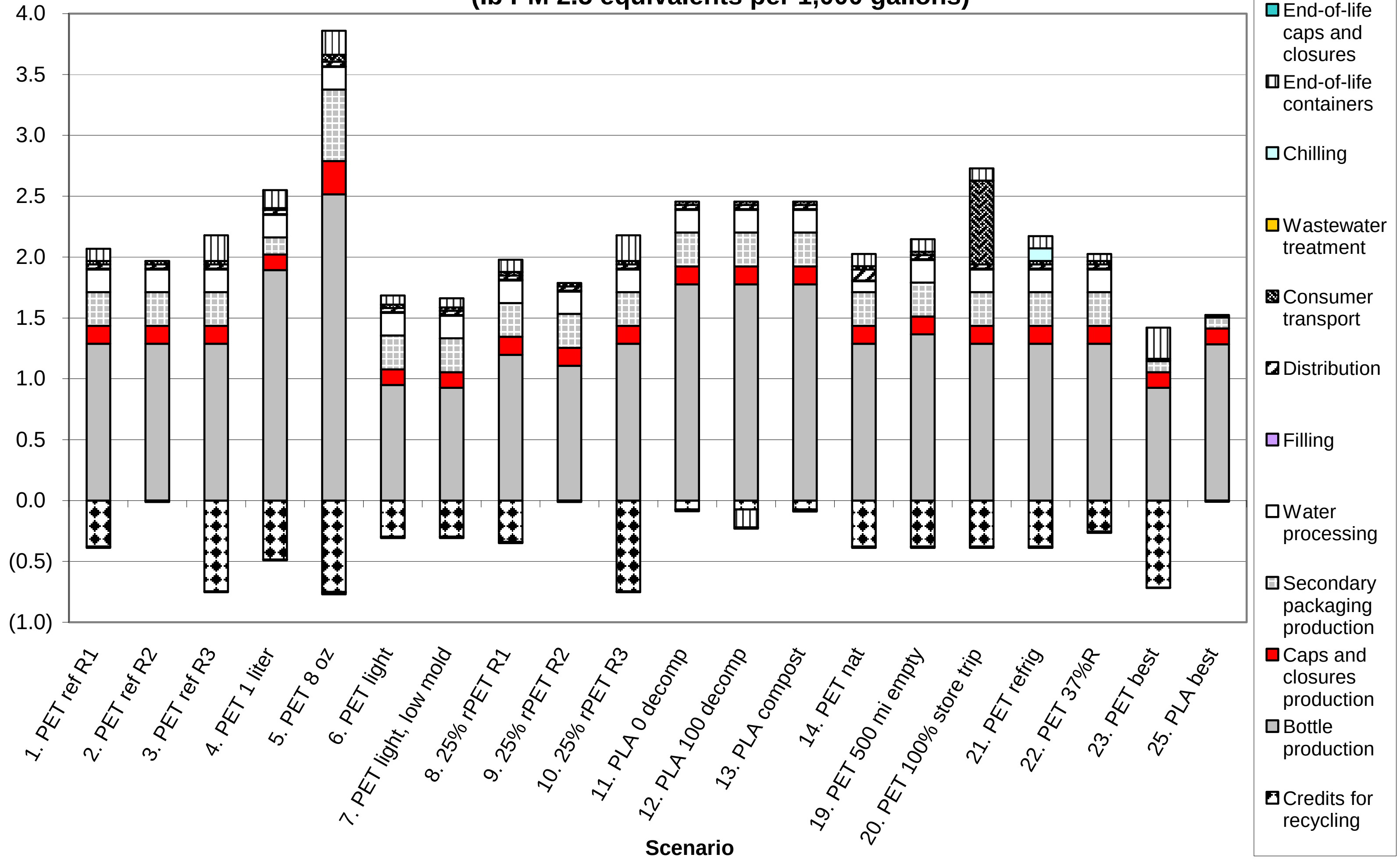

Figure 3-24. Respiratory Effects Potential for Tap and HOD Water Subscenarios (lb PM 2.5 equivalents per 1,000 gallons)

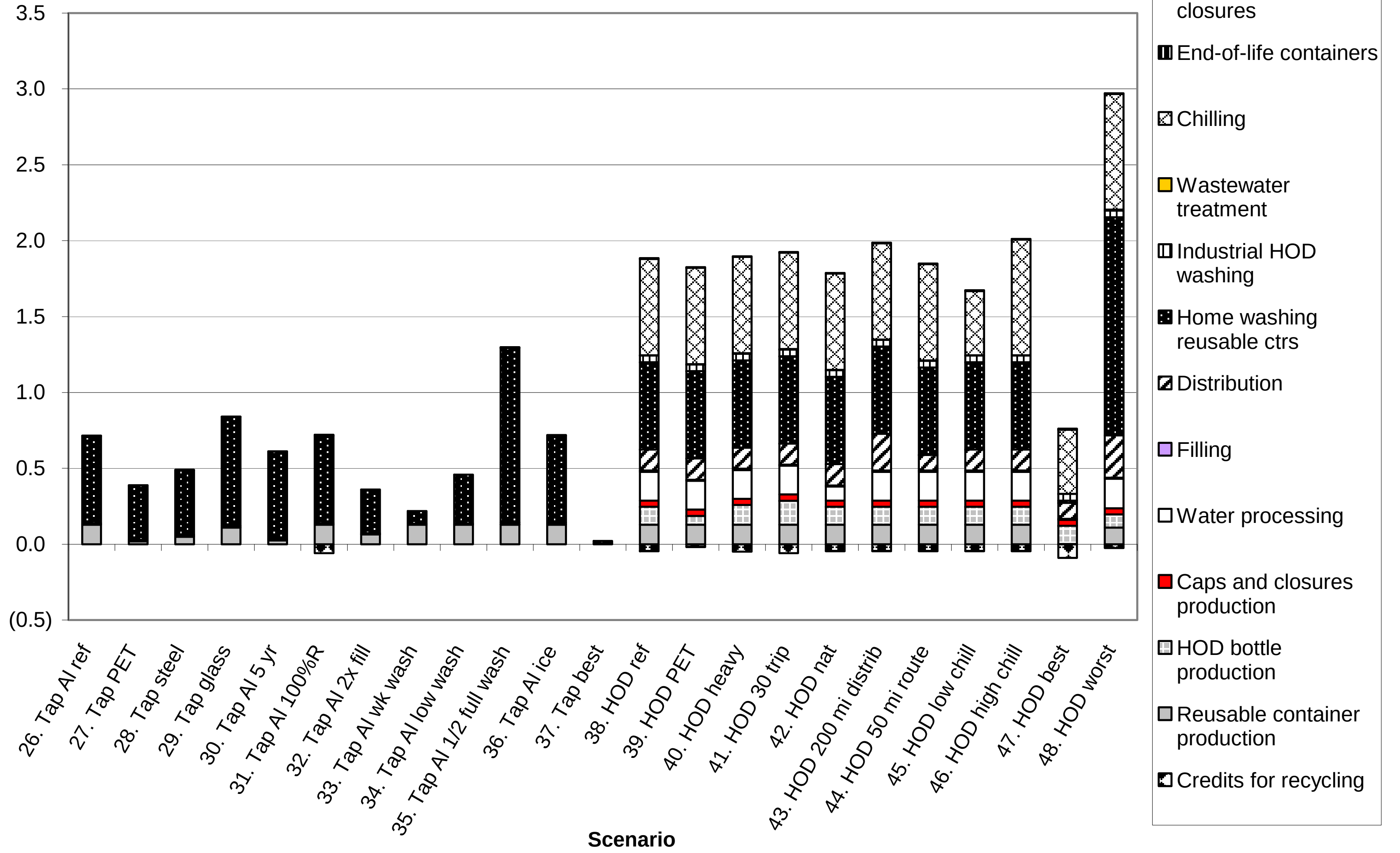

Table 3-10. Smog Potential by Life Cycle Stage for Drinking Water System Scenarios (page 1 of 2)
(lb NOx equivalents per 1,000 gallons)

	Bottled Water												
	PET ref R1	PET ref R2	PET ref R3	PET 1 liter	PET 8 oz	PET light	PET light, low mold	25% rPET R1	25% rPET R2	25% rPET R3	PLA 0 decomp	PLA 100 decomp	PLA compost
Bottled Water Scenarios	1	2	3	4	5	6	7	8	9	10	11	12	13
Production													
Disposable bottle	3.21	3.21	3.21	4.72	6.27	2.36	2.34	2.92	2.64	3.21	2.30	2.30	2.30
Caps and closures	0.24	0.24	0.24	0.21	0.45	0.21	0.21	0.24	0.24	0.24	0.24	0.24	0.24
Secondary packaging	0.39	0.39	0.39	0.19	0.81	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Processes													
Water processing	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Filling	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088
Distribution	0.35	0.35	0.35	0.35	0.36	0.34	0.34	0.35	0.35	0.35	0.35	0.35	0.35
Consumer transport	0.17	0.17	0.17	0.086	0.36	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Wastewater treatment	7.6E-04	7.6E-04	7.6E-04	7.6E-04	7.6E-04	7.6E-04	7.6E-04	7.6E-04	7.6E-04	7.6E-04	7.6E-04	7.6E-04	7.6E-04
Chilling	0	0	0	0	0	0	0	0	0	0	0	0	0
End of life management													
Containers	0.55	0.018	1.06	0.81	1.08	0.41	0.41	0.55	0.018	1.06	0.053	-0.042	0.047
Caps and closures	0.0037	0.0037	0.0037	0.0033	0.0069	0.0033	0.0033	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037
Secondary packaging	0.0034	1.1E-04	0.0064	0.0017	0.0071	0.0034	0.0034	0.0034	1.1E-04	0.0064	0.0034	0.0034	0.0034
Credits for recycling	-0.56	0	-1.10	-0.72	-1.10	-0.44	-0.44	-0.50	0	-1.10	-0.096	-0.096	-0.096
TOTAL	**4.60**	**4.62**	**4.57**	**5.89**	**8.48**	**3.70**	**3.67**	**4.37**	**4.05**	**4.57**	**3.65**	**3.55**	**3.64**

	Bottled Water											
	PET nat	PET Maine nat	PET Fiji nat	PET Fiji free sea	Glass France	PET 500 mi empty	PET 100% store trip	PET refrig	PET 37%R	PET best	PET worst	PLA best
Bottled Water Scenarios	14	15	16	17	18	19	20	21	22	23	24	25
Production												
Disposable bottle	3.21	3.35	6.93	6.93	22.2	3.99	3.21	3.21	3.21	2.34	7.34	1.66
Caps and closures	0.24	0.24	0.39	0.39	2.85	0.24	0.24	0.24	0.24	0.21	0.45	0.21
Secondary packaging	0.39	0.39	0.39	0.39	0.54	0.39	0.39	0.39	0.39	0.14	0.89	0.14
Processes												
Water processing	0.11	0.15	2.2E-04	2.2E-04	0.087	0.23	0.23	0.23	0.23	1.6E-04	0.17	1.6E-04
Filling	0.0088	0.012	0.012	0.012	0.0070	0.0088	0.0088	0.0088	0.0088	0.0088	0.012	0.0088
Distribution	0.90	22.6	41.3	6.57	70.9	0.35	0.35	0.35	0.35	0.14	23.4	0.14
Consumer transport	0.17	0.17	0.17	0.17	0.24	0.17	4.25	0.17	0.17	0.0011	8.98	0.0011
Wastewater treatment	0	0	0	0	0	7.6E-04	7.6E-04	7.6E-04	7.6E-04	0	3.0E-05	0
Chilling	0	0	0	0	0	0	0	0.13	0	0	0.54	0
End of life management												
Containers	0.55	0.55	1.14	1.14	1.08	0.55	0.55	0.55	0.35	1.24	0.092	0.039
Caps and closures	0.0037	0.0037	0.0061	0.0061	0.044	0.0037	0.0037	0.0037	0.0037	0.0033	0.0069	0.0033
Secondary packaging	0.0034	0.0034	0.0034	0.0034	0.0047	0.0034	0.0034	0.0034	0.0034	4.4E-05	0.0078	4.4E-05
Credits for recycling	-0.56	-0.56	-1.05	-1.05	-8.72	-0.56	-0.56	-0.56	-0.37	-1.08	-0.22	0
TOTAL	**5.03**	**27.0**	**49.3**	**14.6**	**89.3**	**5.38**	**8.68**	**4.73**	**4.58**	**3.00**	**41.7**	**2.20**

Table 3-10. Smog Potential by Life Cycle Stage for Drinking Water System Scenarios (page 2 of 2)
(lb NOx equivalents per 1,000 gallons)

	Tap											
Tap Water Scenarios	Tap Al ref 26	Tap PET 27	Tap steel 28	Tap glass 29	Tap Al 5 yr 30	Tap Al 100%R 31	Tap Al 2x fill 32	Tap Al wk wash 33	Tap Al low wash 34	Tap Al 1/2 full wash 35	Tap Al ice 36	Tap best 37
Production												
Reusable drinking container	0.19	0.042	0.11	0.049	0.038	0.19	0.095	0.19	0.19	0.19	0.19	0.0042
Caps and closures	0.0044	0.0039	0.0096	0	8.8E-04	0.0044	0.0022	0.0044	0.0044	0.0044	0.0044	3.9E-04
Processes												
Water processing	0.011	0.0089	0.0094	0.012	0.011	0.011	0.0083	0.0066	0.0073	0.015	0.014	0.0060
Home washing of reusable container	0.64	0.40	0.47	0.80	0.64	0.64	0.32	0.091	0.38	1.28	0.64	0.017
Wastewater treatment	0.0025	0.0015	0.0018	0.0031	0.0025	0.0025	0.0012	3.5E-04	7.1E-04	0.0049	0.0025	3.2E-05
Chilling	0	0	0	0	0	0	0	0	0	0	0	0
End of life management												
Containers	9.7E-04	5.3E-04	0.0014	0.0010	1.9E-04	0.0051	4.8E-04	9.7E-04	9.7E-04	9.7E-04	9.7E-04	5.3E-05
Caps and closures	6.8E-05	6.1E-05	1.5E-04	0	1.4E-05	6.8E-05	3.4E-05	6.8E-05	6.8E-05	6.8E-05	6.8E-05	6.1E-06
Credits for recycling	0	0	0	0	0	-0.081	0	0	0	0	0	0
TOTAL	**0.85**	**0.46**	**0.60**	**0.87**	**0.69**	**0.77**	**0.43**	**0.29**	**0.58**	**1.50**	**0.85**	**0.027**

	HOD										
HOD Water Scenarios	HOD ref 38	HOD PET 39	HOD heavy 40	HOD 30 trip 41	HOD nat 42	HOD 200 mi distrib 43	HOD 50 mi route 44	HOD low chill 45	HOD high chill 46	HOD best 47	HOD worst 48
Production											
Reusable drinking container	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.0042	0.049
HOD bottle	0.15	0.14	0.16	0.20	0.15	0.15	0.15	0.15	0.15	0.15	0.20
Caps and closures	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.056	0.056
Processes											
Water processing	0.23	0.23	0.23	0.23	0.11	0.23	0.23	0.23	0.23	5.9E-04	0.24
Filling	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088
Distribution	1.31	1.31	1.32	1.31	1.31	2.36	0.99	1.31	1.31	0.99	2.69
Home washing of reusable container	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.017	1.60
Industrial HOD washing	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
Wastewater treatment	0.0034	0.0034	0.0034	0.0034	0.0027	0.0034	0.0034	0.0034	0.0034	2.3E-04	0.0071
Chilling	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.52	0.94	0.52	0.94
End of life management											
Containers	0.0067	0.0069	0.0073	0.0086	0.0067	0.0067	0.0067	0.0067	0.0067	0.010	0.0098
Caps and closures	9.3E-04	9.3E-04	9.3E-04	9.3E-04	9.3E-04	9.3E-04	9.3E-04	9.3E-04	9.3E-04	8.7E-04	8.6E-04
Credits for recycling	-0.055	-0.051	-0.060	-0.073	-0.055	-0.055	-0.055	-0.055	-0.055	-0.11	-0.074
TOTAL	**3.39**	**3.38**	**3.41**	**3.43**	**3.27**	**4.43**	**3.07**	**3.13**	**3.55**	**1.71**	**5.79**

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Figure 3-25. Smog Potential for Bottled Water Subscenarios (lb NOx equivalents per 1,000 gallons)

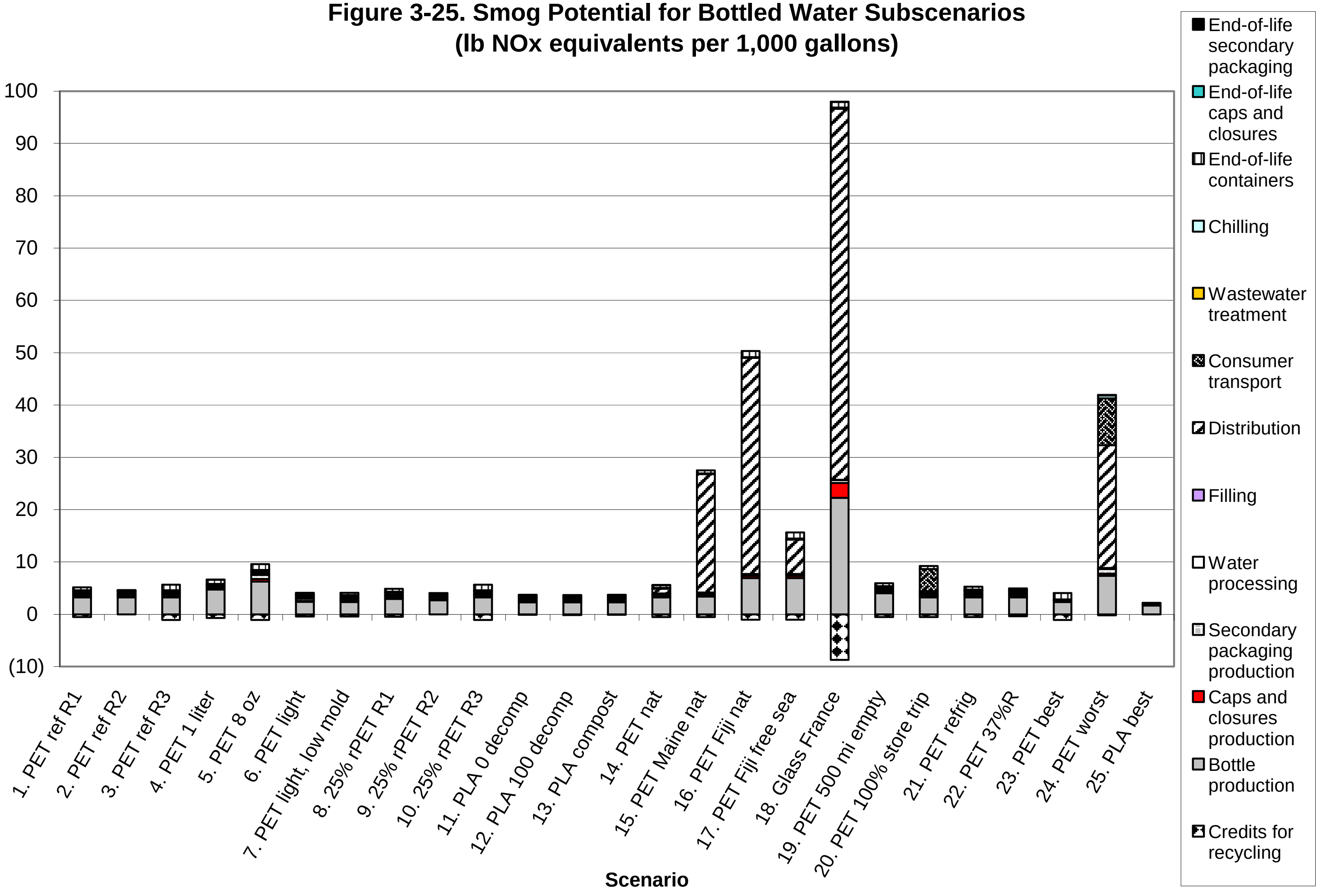
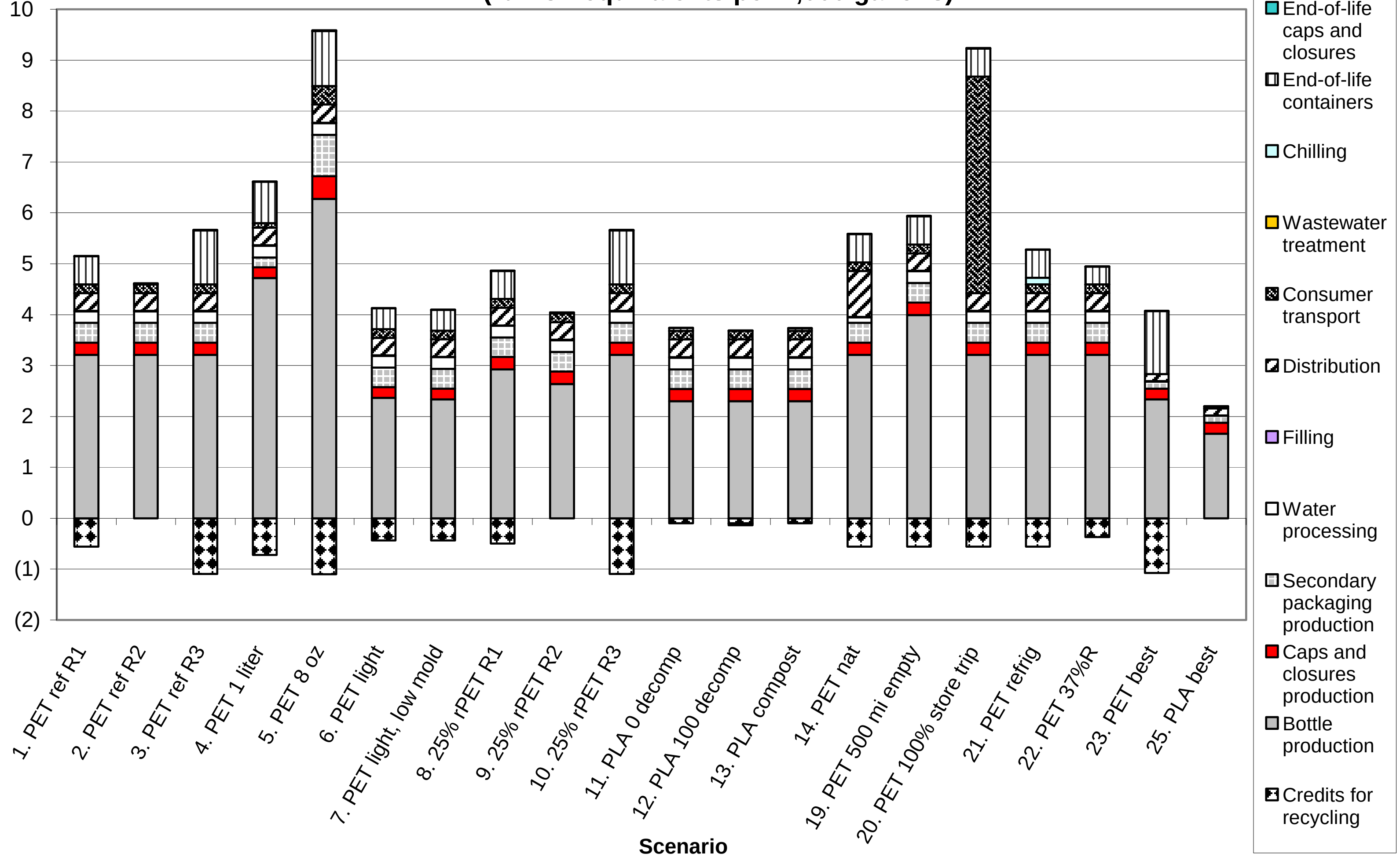


Figure 3-26. Smog Potential for Bottled Water Subscenarios excluding long-distance transport scenarios (lb NOx equivalents per 1,000 gallons)



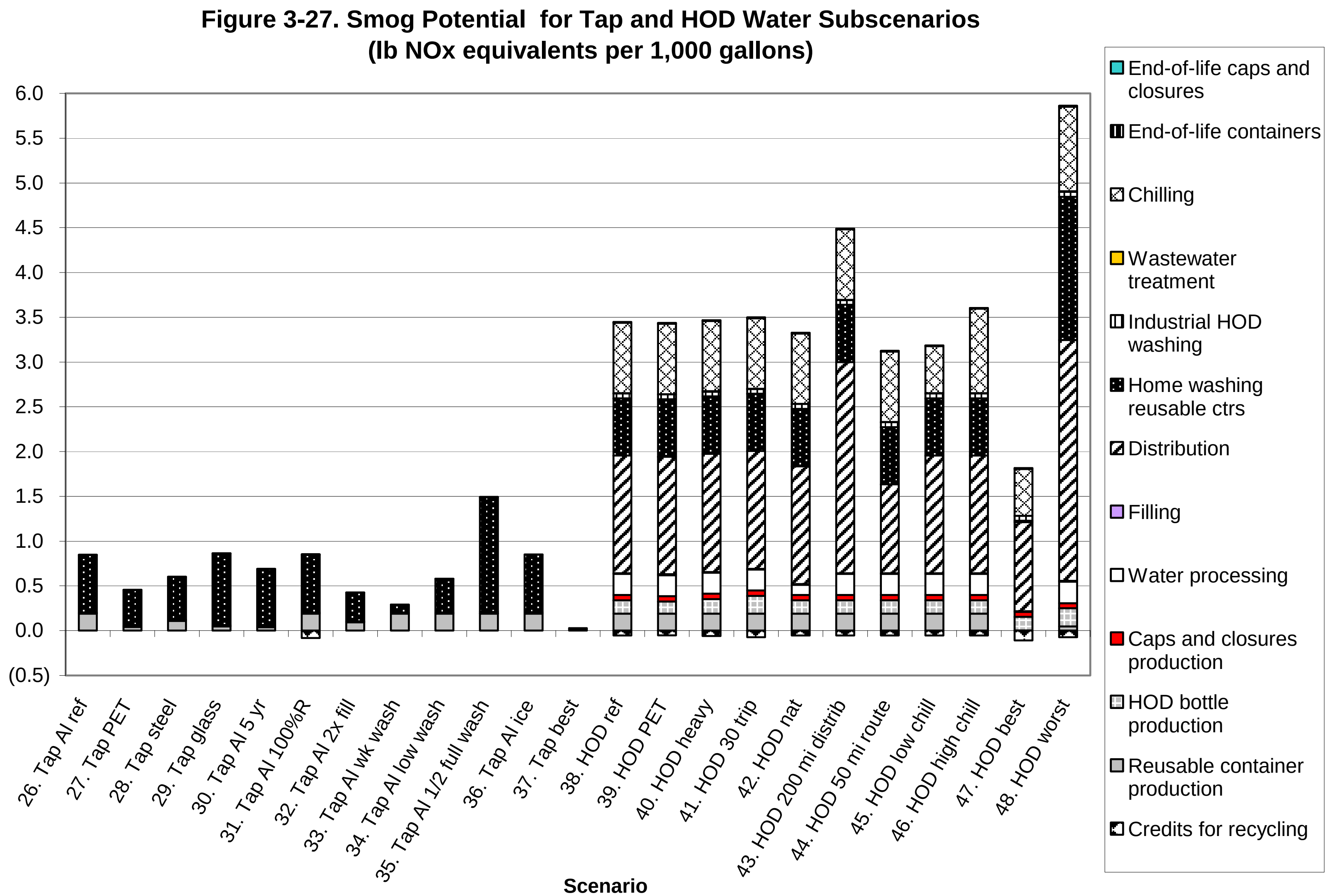


Figure 3-27. Smog Potential for Tap and HOD Water Subscenarios
(lb NOx equivalents per 1,000 gallons)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
(0.5)
26. Tap Al ref
27. Tap PET
28. Tap steel
29. Tap glass
30. Tap Al 5 yr
31. Tap Al 100%R
32. Tap Al 2x fill
33. Tap Al wk wash
34. Tap Al low wash
35. Tap Al 1/2 full wash
36. Tap Al ice
37. Tap best
38. HOD ref
39. HOD PET
40. HOD heavy
41. HOD 30 trip
42. HOD nat
43. HOD 200 mi distrib
44. HOD 50 mi route
45. HOD low chill
46. HOD high chill
47. HOD best
48. HOD worst
Scenario
End-of-life caps and closures
End-of-life containers
Chilling
Wastewater treatment
Industrial HOD washing
Home washing reusable ctrs
Distribution
Filling
Water processing
Caps and closures production
HOD bottle production
Reusable container production
Credits for recycling

Table 3-11. TRACI CHARACTERIZATION FACTORS FOR ATMOSPHERIC AND WATERBORNE EMISSIONS BY IMPACT CATEGORY (as published in SimaPro 7.1 software)

ACIDIFICATION		
Substance Name	**Released to**	**H+ moles eq**
Ammonia	Air	95.5
Hydrogen chloride	Air	44.7
Hydrogen fluoride	Air	81.3
Nitrogen oxides	Air	40.0
Sulfur dioxide	Air	50.8
Sulfur oxides	Air	50.8

CARCINOGENICS		
Substance Name	**Released to**	**kg benzene eq/kg (lb benzene eq/lb)**
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Air	312,962,488
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Water	23,036,735
Dibenzofuran, 2,3,7,8-tetrachloro-	Water	3,895,570
Arsenic	Air	8,497
Benzo(a)pyrene	Air	914
Indeno(1,2,3-cd)pyrene	Air	646
Lead	Water	350
Arsenic, ion	Water	282
Sulfuric acid, dimethyl ester	Air	145
Chromium VI	Air	69.9
Chromium	Air	69.9
Lead	Air	58.2
Cadmium	Air	25.0
Beryllium	Air	11.6
Benzo(a)anthracene	Air	11.2
Ethylene oxide	Air	11.0
Methane, tetrachloro-, CFC-10	Air	7.43
Chrysene	Air	7.17
Ethane, 1,2-dibromo-	Air	5.77
Toluene, 2,4-dinitro-	Air	2.47
Ethane, 1,2-dichloro-	Air	2.29
Ethane, 1,1,2-trichloro-	Air	1.83
Nickel	Air	1.51
Benzene	Air	1.00
Benzene	Water	1.00
Chloroform	Air	0.81
Ethene, tetrachloro-	Air	0.72
Benzyl chloride	Air	0.56
Butadiene	Air	0.41
Hydrazine, methyl-	Air	0.41
Propylene oxide	Air	0.32
Methane, monochloro-, R-40	Air	0.29
Methane, monochloro-, R-40	Water	0.22
Bromoform	Air	0.18
Methane, dichloro-, HCC-30	Air	0.14
Phthalate, dioctyl-	Air	0.13
Ethene, trichloro-	Air	0.064
Acetaldehyde	Air	0.0044
Formaldehyde	Air	0.0037
Isophorone	Air	1.6E-04
Chromium, ion	Water	5.6E-46
Chromium VI	Water	5.6E-46
Chromium	Water	5.6E-46

Beryllium	Water	1.1E-46
Nickel, ion	Water	1.6E-47
Nickel	Water	1.6E-47
Cadmium, ion	Water	5.4E-49

ECOTOXICITY		
Substance Name	**Released to**	**kg 2,4-D eq/kg (lb 2,4-D eq/lb)**
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Water	104,919
Copper	Air	21,664
Copper, ion	Water	11,537
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Air	8,052
Nickel	Air	7,836
Silver	Water	7,535
Silver, ion	Water	7,535
Zinc	Air	5,879
Mercury	Water	3,114
Nickel	Water	2,671
Nickel, ion	Water	2,671
Zinc	Water	2,052
Zinc, ion	Water	2,052
Aluminum	Water	1,844
Selenium	Air	1,528
Selenium	Water	1,076
Chromium	Air	1,049
Chromium VI	Air	1,049
Chromium	Water	781
Chromium VI	Water	781
Chromium, ion	Water	781
Thallium	Water	611
Arsenic, ion	Water	246
Indeno(1,2,3-cd)pyrene	Air	243
Arsenic	Air	209
Mercury	Air	16.3
Cadmium, ion	Water	10.4
m-Xylene	Water	7.68
Acrolein	Air	7.12
Styrene	Water	6.51
Cadmium	Air	6.26
Benzene, ethyl-	Water	3.27
Hydrogen chloride	Air	3.19
Xylene	Water	2.53
Lead	Water	2.37
Chrysene	Air	2.16
Benzene	Water	1.63
Toluene	Water	1.63
Lead	Air	1.44
Acetophenone	Air	1.03
Methane, bromo-, Halon 1001	Air	0.83
Methane, monochloro-, R-40	Water	0.41
Phenol	Water	0.35
Ammonia	Water	0.18
Ethane, 1,1,2-trichloro-	Air	0.15
Benzene, chloro-	Air	0.15
Acenaphthene	Air	0.10
Ammonia	Air	0.074
Benzo(a)pyrene	Air	0.069

Phenol	Air	0.054
Anthracene	Air	0.053
Formaldehyde	Air	0.051
Ethane, 1,2-dichloro-	Air	0.046
Benzo(a)anthracene	Air	0.045
Chloroform	Air	0.040
Ethene, tetrachloro-	Air	0.019
Methanol	Air	0.019
Methane, dichloro-, HCC-30	Air	0.014
Methane, tetrachloro-, CFC-10	Air	0.012
Acetone	Water	0.0096
Methyl ethyl ketone	Air	0.0096
Benzene	Air	0.0063
Methane, monochloro-, R-40	Air	0.0051
Acetaldehyde	Air	0.0034
Benzene, ethyl-	Air	0.0034
t-Butyl methyl ether	Air	0.0029
Toluene	Air	0.0025
Xylene	Air	0.0016
Styrene	Air	0.0016
Methane, dichlorodifluoro-, CFC-12	Air	0.0015
Phthalate, n-dioctyl-	Air	0.0011
Ethene, trichloro-	Air	0.0011
Methane, chlorodifluoro-, HCFC-22	Air	3.2E-05
Propene	Air	2.9E-06
Hexane	Air	1.3E-06

EUTROPHICATION

Substance Name	**Released to**	**kg N eq/kg (lb N eq/lb)**
Phosphorus	Water	7.29
Phosphate	Water	2.38
Phosphorus	Air	1.12
Nitrogen	Water	0.99
Ammonium, ion	Water	0.78
Nitrate	Water	0.24
Ammonia	Air	0.12
BOD5, Biological Oxygen Demand	Water	0.050
COD, Chemical Oxygen Demand	Water	0.050
Nitrogen oxides	Air	0.044

GLOBAL WARMING

Substance Name	**Released to**	**kg CO2 eq/kg (lb CO2 eq/lb)**
Methane, dichlorodifluoro-, CFC-12	Air	10,720
Methane, tetrafluoro-, CFC-14	Air	5,820
Methane, chlorodifluoro-, HCFC-22	Air	1,780
Methane, tetrachloro-, CFC-10	Air	1,380
Dinitrogen monoxide	Air	300
Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123	Air	76.0
Chloroform	Air	30.0
Methane	Air	23.0
Methane, monochloro-, R-40	Air	16.0
Methane, dichloro-, HCC-30	Air	10.0
Methane, bromo-, Halon 1001	Air	5.00
Carbon monoxide	Air	1.57
Carbon dioxide, fossil	Air	1.00

NON-CARCINOGENICS		
Substance Name	**Released to**	**kg toluene eq/kg (lb toluene eq/lb)**
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Air	346,000,000,000
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Water	22,044,573,808
Lead	Water	11,303,405
Antimony	Air	2,801,491
Lead	Air	2,173,733
Cadmium, ion	Water	2,013,978
Mercury	Water	943,040
Arsenic	Air	469,379
Cadmium	Air	387,350
Beryllium	Air	167,536
Mercury	Air	99,912
Nickel	Air	71,919
Selenium	Air	71,282
Thallium	Water	64,036
Chromium	Air	57,677
Chromium VI	Air	57,677
Cobalt	Air	29,043
Arsenic, ion	Water	13,502
Copper	Air	13,215
Zinc	Air	10,247
Manganese	Air	6,093
Copper, ion	Water	5,903
Antimony	Water	4,206
Ethane, 1,2-dibromo-	Air	2,457
Acrolein	Air	2,366
Methane, tetrachloro-, CFC-10	Air	1,767
Selenium	Water	1,419
Hydrogen cyanide	Air	1,374
Cyanide	Air	1,374
Cyanide	Water	1,253
Methane, bromo-, Halon 1001	Air	1,169
Beryllium	Water	1,047
Molybdenum	Water	828
Ethylene oxide	Air	619
Chromium	Water	583
Chromium VI	Water	583
Chromium, ion	Water	583
Vanadium	Water	547
Silver	Water	539
Ethane, 1,1,2-trichloro-	Air	204
Carbon disulfide	Air	188
Nickel	Water	92.7
Nickel, ion	Water	92.7
Toluene, 2,4-dinitro-	Air	75.0
Ethene, tetrachloro-	Air	74.9
Bromoform	Air	57.5
Barium	Water	57.3
Furan	Water	54.0
Methane, monochloro-, R-40	Air	39.4
Furan	Air	36.3
Naphthalene	Water	24.3
Benzyl chloride	Air	23.9
Methane, monochloro-, R-40	Water	23.2
Aluminum	Water	20.5
Zinc	Water	17.9

Zinc, ion	Water	17.9
Phthalate, dioctyl-	Air	17.4
Tin	Water	15.5
Benzene	Air	14.6
Naphthalene	Air	13.6
Chloroform	Air	12.5
Manganese	Water	11.8
Benzene	Water	9.61
Ethane, 1,2-dichloro-	Air	7.17
Fluoranthene	Air	5.38
Formaldehyde	Air	5.07
Acetophenone	Air	4.36
Acetaldehyde	Air	4.25
Methane, dichlorodifluoro-, CFC-12	Air	3.80
Ammonia	Air	3.21
Biphenyl	Water	2.53
Vinyl acetate	Air	1.93
Benzene, chloro-	Air	1.79
Fluorene	Air	1.77
Butadiene	Air	1.33
Methane, dichloro-, HCC-30	Air	1.13
p-Xylene	Water	1.02
Toluene	Air	1.00
Toluene	Water	1.00
Methyl ethyl ketone	Air	0.94
Ethene, trichloro-	Air	0.93
m-Xylene	Water	0.86
o-Cresol	Water	0.71
Hexane	Air	0.64
Propylene oxide	Air	0.63
Biphenyl	Air	0.62
Pyrene	Air	0.57
4-Methyl-2-pentanone	Water	0.52
Cumene	Air	0.33
Styrene	Water	0.29
Methane, chlorodifluoro-, HCFC-22	Air	0.22
Hydrogen chloride	Air	0.21
Acenaphthene	Air	0.18
Acetone	Water	0.17
Methacrylic acid, methyl ester	Air	0.15
Ethane, chloro-	Air	0.15
Acetic acid, methyl ester	Air	0.11
t-Butyl methyl ether	Air	0.093
p-Cresol	Water	0.080
Methanol	Air	0.074
Ammonia	Water	0.057
Phenol	Air	0.050
Xylene	Water	0.047
Styrene	Air	0.031
Xylene	Air	0.025
Isophorone	Air	0.020
Anthracene	Air	0.0083
Propene	Air	0.0077
2-Propanol	Water	0.0058
Phenol	Water	0.0038
Benzoic acid	Water	0.0029
Cobalt	Water	2.6E-43

OZONE DEPLETION		
Substance Name	**Released to**	**kg CFC-11 eq/kg (lb CFC-11 eq/lb)**
Methane, dichlorodifluoro-, CFC-12	Air	1.00
Methane, tetrachloro-, CFC-10	Air	0.73
Methane, bromo-, Halon 1001	Air	0.38
Methane, chlorodifluoro-, HCFC-22	Air	0.050
Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123	Air	0.020

RESPIRATORY EFFECTS		
Substance Name	**Released to**	**kg PM2.5 eq/kg (lb PM2.5 eq/lb)**
Particulates, < 2.5 um	Air	1.00
Particulates, > 10 um	Air	0.60
TSP	Air	0.33
Sulfur dioxide	Air	0.24
Nitrogen oxides	Air	0.042

SMOG		
Substance Name	**Released to**	**kg NOx eq/kg (lb NOx eq/lb)**
Furan	Air	2.85
Butadiene	Air	2.60
Propene	Air	2.47
Ethene	Air	1.98
Formaldehyde	Air	1.81
Aldehydes, C7	Air	1.71
Aldehydes, C3	Air	1.65
Acrolein	Air	1.61
Aldehydes, C8	Air	1.48
Acetaldehyde	Air	1.44
Aldehydes, C4	Air	1.40
Aldehydes, C5	Air	1.21
Aldehydes, C6	Air	1.01
Nitrogen oxides	Air	1.00
Toluene	Air	0.83
VOC, volatile organic compounds	Air	0.78
Phenol	Air	0.74
Naphthalene	Air	0.61
Benzene, ethyl-	Air	0.59
Styrene	Air	0.50
Cumene	Air	0.49
Hexane	Air	0.34
t-Butyl methyl ether	Air	0.27
Benzene	Air	0.20
Methanol	Air	0.20
Benzene, chloro-	Air	0.16
Acetic acid	Air	0.13
Propylene oxide	Air	0.084
Acetic acid, methyl ester	Air	0.023
Ethene, tetrachloro-	Air	0.023
Methane, dichloro-, HCC-30	Air	0.019
Ethylene oxide	Air	0.017
Carbon monoxide	Air	0.013
Methane, bromo-, Halon 1001	Air	0.0048
Methane, fossil	Air	0.0030
Methane	Air	0.0030
Ethene, trichloro-	Air	2.1E-04

CHAPTER 4

INTERPRETATION OF RESULTS

INTRODUCTION

The life cycle inventory (LCI) and life cycle impact assessment (LCIA) chapters include discussion about the main contributors to the results for the individual drinking water delivery systems. In this chapter, the ranges of results for the drinking water subscenarios are summarized and compared across the range of subscenarios evaluated for each system.

The ranges of results shown in this chapter include all of the 48 subscenarios described in Table 2-9. The majority of the subscenarios (20 of the 48 subscenarios) were run on variations of PET bottled water systems. Four PLA bottle subscenarios and one glass bottle subscenario were also evaluated. For drinking water systems utilizing reusable containers, there were 12 subscenarios for tap water consumption using a variety of reusable drinking containers and 11 subscenarios for HOD water consumed from reusable containers. The majority of the tap and HOD scenarios (17 of the 23 scenarios) were based on use of a reusable aluminum drinking container with a lid (such as the widely used SIGG bottle).

Because more variations of the Oregon PET bottle system were evaluated than any other drinking water system, the “Bottled – OR” results in the figures in this chapter show a wider range than other drinking water systems. The Bottled - OR results include PET bottle sizes ranging from 8 ounces to 1 liter and encompass variations in bottle weights, recycled content, recycling levels, and recycling methodologies, as well as several PLA bottle scenarios.

An important issue with LCI results is whether two numbers are actually different from one another. If the error or variability in the data is sufficiently large, it cannot be concluded that the two numbers are truly different. A statistical analysis that yields clear numerical answers would be ideal, but LCI data, which are typically based on a limited number of data sets for each unit process, are not suited to application of formal statistics, which pertain to random samples from large populations that result in “normal curve” distributions. However, based on sample statistical calculations and the professional judgment of the analysts, the following guidance is provided for interpretation of LCI results presented in this report: In order for two systems’ results to be considered significantly different, there must be a minimum percent difference of 10% in results for energy and postconsumer solid waste weight and 25% for emissions.[37]

[37] The percent difference between system results is calculated as the difference between the two systems’ results divided by the average of the two systems’ results.

LCIA results are based on LCI emissions data, so a 25% difference would be the minimum difference considered meaningful for potential impact results if all the uncertainty were due to the uncertainty in the LCI data. However, in addition to the uncertainty of the LCI emissions data, there is additional uncertainty associated with the application of LCIA methodologies to aggregated LCI emissions, as described in Chapter 3 in the Limitations section. For example, two systems may release the same total amount of the same substance, but one quantity may represent a single high-concentration release to a stressed environment while the other quantity may represent the aggregate of many small dilute releases to environments that are well below threshold limits for the released substance. The actual impacts would likely be very different for these two scenarios, but the life cycle inventory does not track the temporal and spatial resolution or concentrations of releases in sufficient detail for the LCIA methodology to model the aggregated emission quantities differently. Therefore, no specific guidelines are given for determining with confidence that differences in potential impacts are sufficient to be considered significant differences.

LIFE CYCLE INVENTORY RESULTS

Figures 4-1 through 4-3 display the ranges of results for energy and solid wastes for the drinking water systems. Each figure shows the full range of results for *all* subscenarios evaluated, including the subscenarios referred to as “best case” and “worst case” scenarios (e.g., those combinations of parameters that are expected to produce the highest and lowest energy and solid waste results). Data uncertainty margins have been added to Figures 4-1 through 4-3 to reflect the uncertainties in the energy and solid waste data. For example, the lower ends of the energy bands have been expanded to minus 10% of the lowest point value, and the higher ends of the energy bands have been expanded to plus 10% of the highest point value.

In each figure, the bar “Bottled – Long Haul” includes the range of results for bottled water systems that are imported to Oregon from other countries or from out of state. The bar labeled “Bottled – OR” includes results for all bottled water scenarios that are bottled and transported within Oregon, including water bottled in PET and PLA bottles.

Figure 4-1. Range of Net Energy for Subscenarios Evaluated (adjusted for +/- 10% uncertainty of energy results)

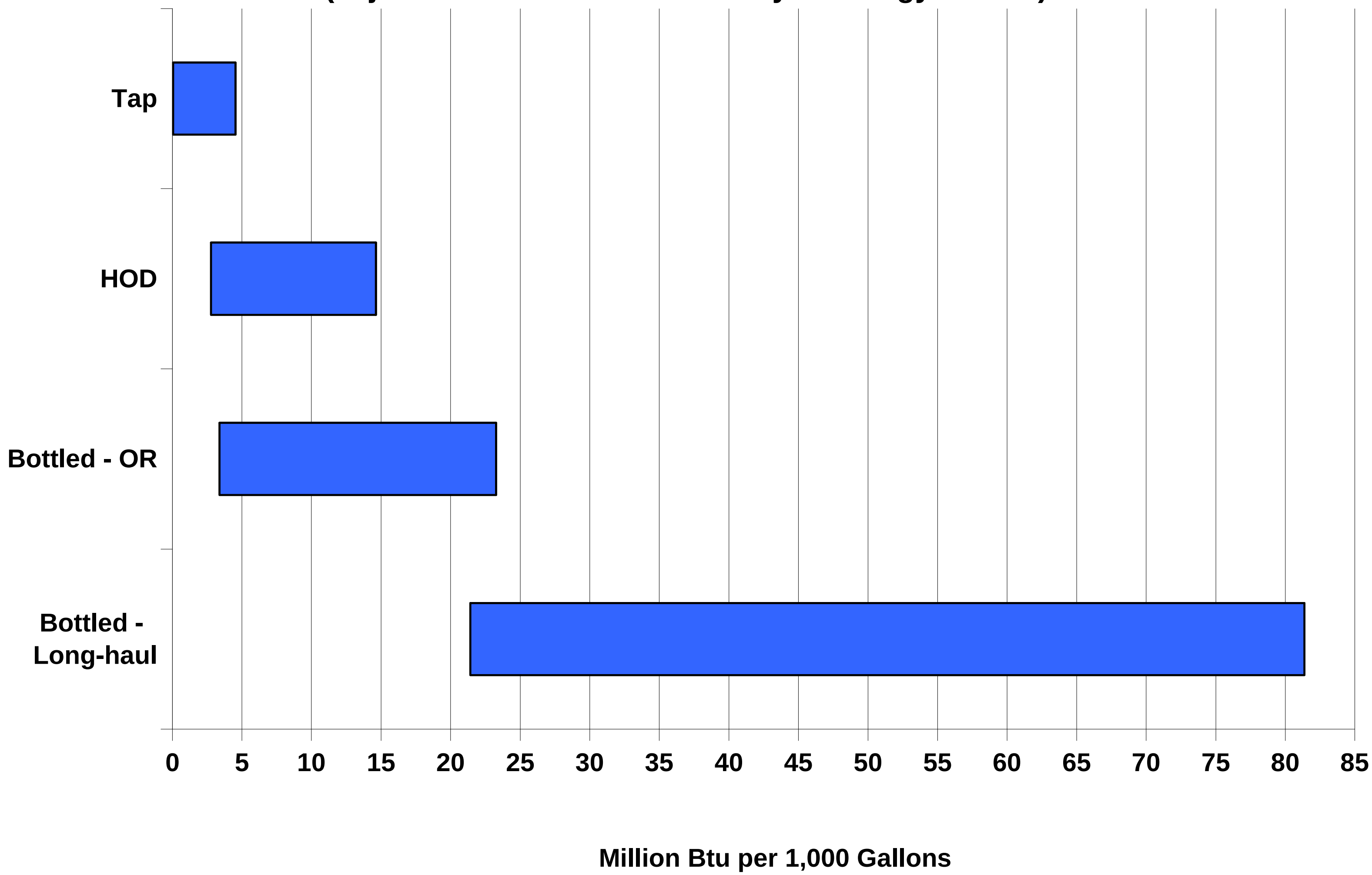


Figure 4-2. Range of Solid Waste by Weight for Subscenarios Evaluated (adjusted for +/- 10% uncertainty for weight of postconsumer solid waste and +/- 25% uncertainty for weight of industrial solid waste)

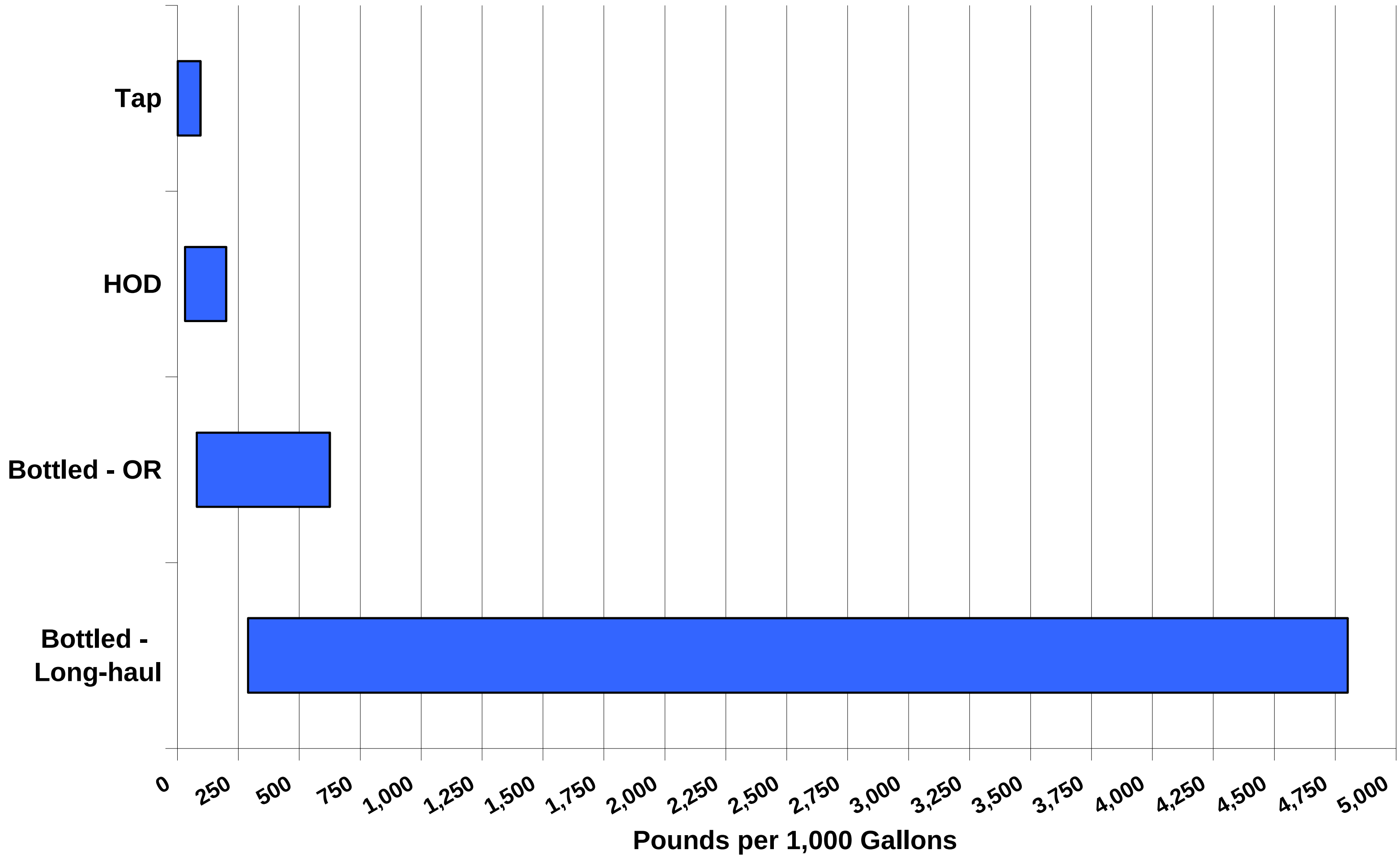
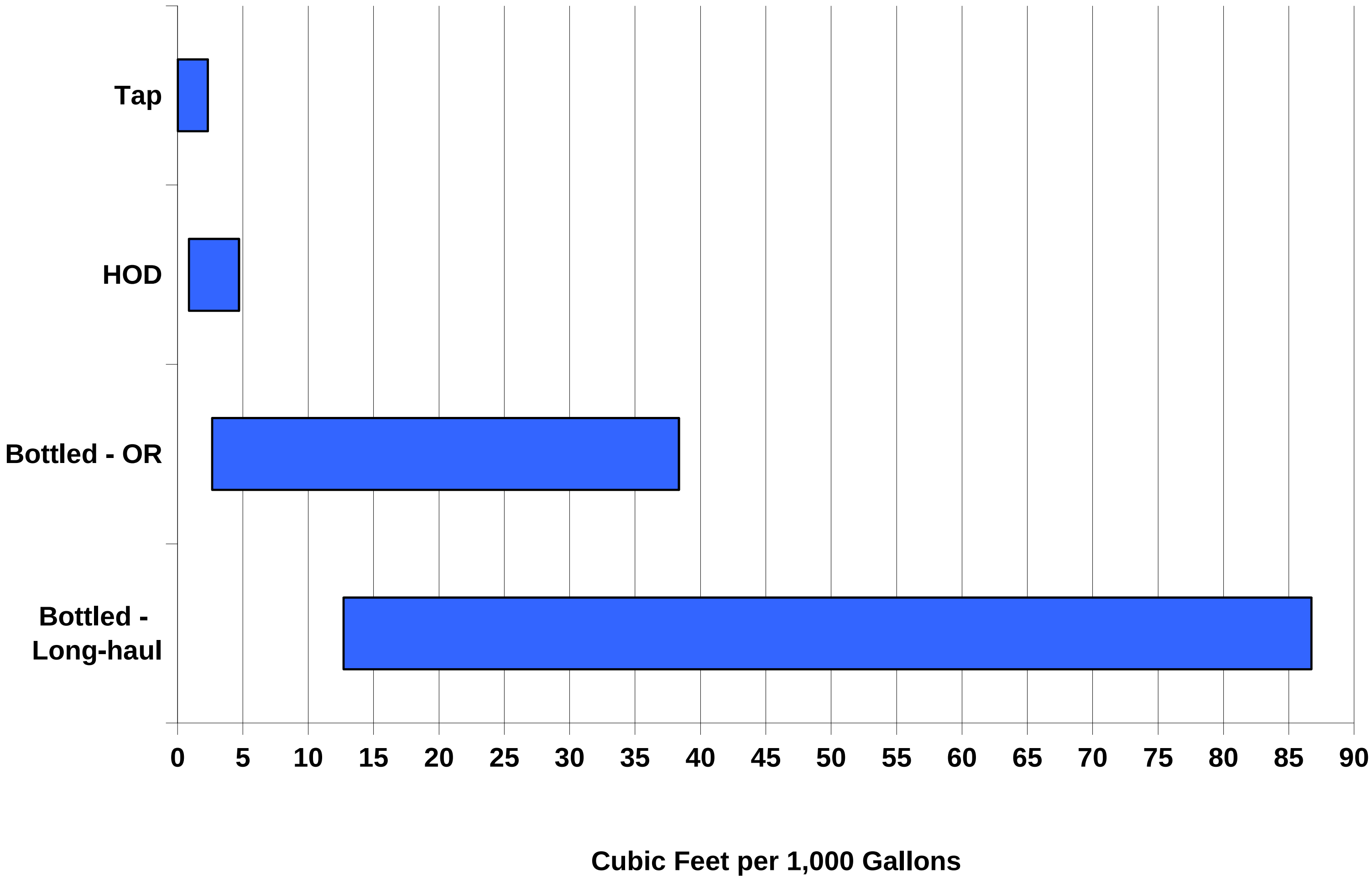


Figure 4-3. Range of Compacted Solid Waste Volume for Subscenarios Evaluated (adjusted for +/- 25% uncertainty for solid waste volume results)



Energy Results

Figure 4-1 shows that when the full range of subscenarios are considered, the imported water has by far the highest energy burdens. This is due to the long transportation distances and the inclusion of results for imported water packaged in glass, which is a much heavier package and thus more energy intensive to transport.

For the Oregon bottled water (excluding long-haul water), the PET subscenarios include bottles of different sizes and weights with different levels of recycled content and end-of-life recycling, as well as several PLA bottle scenarios. The high end of the results corresponds to scenario 5 for water packaged in 8 ounce PET bottles. Smaller containers have a higher ratio of packaging weight to volume of water in the bottle, and more trips to the store are required per 1,000 gallons when purchasing smaller bottles of water a case at a time. The low end of the results is for scenario 23 with a future lightweighted bottle that is not currently in the marketplace[38] combined with a 100% recycling rate.

Within the Oregon bottled water results, the range of results for PLA bottles is very small since only 16.9 ounce PLA bottles were evaluated in the subscenarios. No recycled content or end-of-life recycling was evaluated for PLA bottles; however, the results include subscenarios with different assumptions about decomposition of landfilled bottles and a scenario for PLA composting. The PLA system energy range falls within the low end of the range of energy results for the PET bottle subscenarios.

The energy comparisons can be summarized as follows:

- All tap and HOD scenarios show lower energy than all long-haul water scenarios. As noted above, the “best case” low end results for the Oregon bottled water scenarios (excluding long-haul water) are for a future lightweighted bottle not currently in the marketplace, combined with 100% bottle recycling.
- When *existing* Oregon bottled water subscenarios are compared to tap subscenarios, the energy for tap subscenarios is lower in all cases.
- When existing Oregon bottled water subscenarios are compared to HOD subscenarios, there is overlap in many cases so that neither system can generally be considered to have lower energy results.
- The lowest energy results for the HOD system are for the most favorable drinking container washing scenario (32-ounce container filled twice daily and washed once weekly in a low water use dishwasher loaded to full capacity). Other tap and HOD subscenarios are based on a smaller container washed after each use in a high water use dishwasher that is run fully loaded. The tap system subscenarios have lower energy results than the HOD subscenarios in all cases but one: the comparison of the best case HOD scenario with the most inefficient tap container washing scenario

[38] Weight of Nestle Waters Pure Life bottle for 2011, reported in article “Pepsi to Pare Plastic for Bottled Water.” Wall Street Journal. March 25, 2009.

(small container washed after each use in a high water use dishwasher that is run half full). Assuming a consumer's container washing practices are not influenced by the type of water served in the container (tap versus HOD), it is reasonable to conclude that tap water systems have lower energy requirements than HOD water systems.

Solid Waste Results

As with the energy results, the solid waste results for long-haul bottled water in Figure 4-2 are strongly influenced by the inclusion of glass bottles. Within the Oregon bottled water results, the range of solid waste results includes PET bottles evaluated at a range of bottle weights, cap weights, secondary packaging, and recycling of bottles, and a PLA composting scenario that permanently diverts the postconsumer material from landfill disposal. The lowest bottled water solid waste results are for the future lightweighted PET bottle at 100% recycling, then the PLA bottle at 100% composting.

As expected, the HOD and tap water systems do not produce much solid waste since these drinking water systems utilize drinking water containers that are used many times over their useful life. The HOD bottles are also refilled and reused multiple times before they are retired from service and recycled; however, the solid waste results for the HOD systems do include the weight of disposed HOD plastic caps that are assumed to be replaced after each use cycle of an HOD bottle.

The solid waste volume results for the systems are directly related to the amount of postconsumer material that goes to landfill and the degree to which the material compacts in the landfill. The choice of recycling allocation method also influences the solid waste weight and volume results. The majority of subscenarios used the open-loop recycling method (method 1), in which half of the disposal burdens for the recycled bottles are allocated to the bottle system and half to the system using the recycled material. Recycling methods 2 and 3 allocate all disposal burdens for recycled material to the system using the recycled material, so the subscenarios using methods 2 and 3 show lower solid waste results than the subscenarios using method 1.

The following solid waste observations are made:

- In nearly all solid waste comparisons, both the tap and HOD systems have lower solid waste than the bottled water systems (long-haul and Oregon bottled water), although there are a few exceptions. The HOD worst case scenario overlaps with several Oregon bottled water solid waste subscenarios. Excluding the HOD worst case, the only other comparisons where bottled water solid wastes are lower than tap and HOD solid wastes are the PLA bottle at 100% composting and the future lightweighted PET bottle at 100% recycling.
- The lowest solid waste results for the HOD system are for the most favorable drinking container washing scenario (32-ounce container filled twice daily and washed once weekly in a low water use dishwasher loaded

to full capacity). Other tap and HOD subscenarios are based on a smaller container washed after each use in a high water use dishwasher that is run fully loaded. There is some overlap in solid waste results when tap scenarios are compared to the best case HOD washing scenario; however, when tap subscenarios are compared to all other HOD subscenarios, the tap systems have lower solid waste.

LIFE CYCLE IMPACT ASSESSMENT RESULTS

Figures 4-4 through 4-12 display the ranges of results for the impact categories evaluated for the drinking water systems. The major factors contributing to each impact for each drinking water system have been discussed in Chapter 3.

Long-Haul Bottled Water Compared to Oregon Bottled Water

When comparing the results for long-haul bottled water and Oregon bottled water, Figures 4-4 through 4-12 show that in most impact categories there is overlap or very small gaps between the ranges of results for long-haul and Oregon bottled water. For the impact categories of carcinogenic potential, eutrophication, non-carcinogens, and ozone depletion, there is overlap between the low end of the long-haul bottled water results and the high end of the Oregon bottled water results. In the remaining categories, the results for all Oregon bottled water scenarios are lower than the results for all long-haul scenarios, although the gap is very small for ecotoxicity, global warming potential, and respiratory effects. Results for acidification potential and smog potential show larger gaps between the high results for Oregon bottled water and the lowest results for long-haul bottled water.

It should be noted that differences between the long-haul and Oregon bottled water scenarios are not limited to differences in transportation. As shown in the list of bottled water subscenarios (Table 2-9), there are also differences in some of the bottle systems modeled for domestic and imported water. Both systems include results for 16.9-ounce (500 ml) PET bottles, although some PET bottles used for imported water are significantly heavier than the same size domestic bottles. The long-haul subscenarios also include glass bottles, which are not included in the Oregon bottled water subscenarios since glass bottles are used primarily for imported water. The differences in bottle type and weight also contribute to the differences in impact results for the long-haul and Oregon bottled water systems.

Long-Haul Bottled Water Compared to Tap Water

Across all the impacts evaluated in this analysis, there are no cases where there is overlap between the high end of the tap results and the low end of the long-haul bottled water results. For all impact categories, results for all tap water scenarios are lower than all long-haul bottled water scenarios.

Oregon Bottled Water Compared to Tap Water

For about half of the impact categories, there is no overlap between the high end of the tap results and the low end of the Oregon bottled water results. However, there is some overlap in results for carcinogenics, global warming potential, non-carcinogenic, respiratory effects, and eutrophication (with phosphate detergent use for home washing). The high end results for the tap system are for the scenario in which the drinking container is washed after each use in a high water use dishwasher that is run when it is half full, and the low end results for the Oregon bottled water are for a 9.8 gram bottle that is not anticipated to be on the market until 2011, combined with 100% container recycling. When the 2011 bottle scenarios are excluded, results for all tap scenarios, even with inefficient dishwasher operation, are lower than all the other Oregon bottled water scenarios.

Long-Haul Bottled Water Compared to HOD Water

There are no impact category results where there is overlap between the high end of the HOD results and the low end of the long-haul bottled water results. Results for all HOD scenarios are lower than all long-haul bottled water scenarios.

Oregon Bottled Water Compared to HOD Water

The high end of the HOD results overlaps the low end of the Oregon bottled water results in every impact category. The low end of the Oregon PET bottled water results are for the lowest weight PET bottle (not yet in the marketplace) at 100% recycling, while the high end results for the HOD system represent a scenario in which the drinking containers are washed after each use in a high water use dishwasher that is run when it is only half full. When these two extreme scenarios are excluded, there is still overlap between many of the HOD and Oregon bottled water scenarios.

Tap Water compared to HOD Water.

When the full range of tap results are compared to the full range of HOD results, ecotoxicity and smog are the only impacts for which all tap scenario results are lower than all HOD scenario results. All other impacts show overlap between the results for the two systems. For both the tap and HOD systems, the worst case scenario is based on the water being consumed from a drinking container washed after each use in a high water use dishwasher that is run half full, and the best case is based on the water being consumed from a 32-ounce container that is filled twice daily and washed once weekly in a low water use dishwasher loaded to full capacity. The overlap occurs when the best case HOD drinking container washing scenario is compared to the worst case tap drinking container washing scenario. It is reasonable to assume that a consumer will use the same washing practices for washing reusable drinking containers regardless of whether the water consumed from the container is tap water or HOD water. If the same washing parameters are used for the drinking container, all results for tap water are lower than all results for HOD water.

Observations regarding impact comparisons between the different drinking water systems can be summarized as follows:

- Within the bottled water subscenarios evaluated, the ranges of impact results for long-haul bottled water and Oregon bottled water overlap or show small gaps for most impact categories.
- For the subscenarios evaluated in this study, all tap and HOD scenario results are lower in all impact categories than the long-haul bottle scenarios.
- The tap system subscenarios evaluated all have lower impacts than *existing* Oregon bottled water scenarios. The future lightweighted bottle combined with very high bottle recycling rates has the potential to compare favorably with tap scenarios with inefficient container washing practices.
- There are many cases of overlap in the HOD subscenario results and the Oregon bottled water subscenario results, even when the best and worst case scenarios are excluded for each system. Therefore, no general statements can be made about which of these systems has lower environmental impacts.
- While there is some overlap in the results for tap and HOD system subscenarios, these occur only for the worst case tap container washing scenario compared to the best case HOD drinking container washing scenario. If one assumes that a consumer will use the same container washing practices when consuming either type of water, then the tap system results are lower than the HOD system results across the range of subscenarios evaluated.

Figure 4-4. Range in Acidification Potential for Subscenarios Evaluated

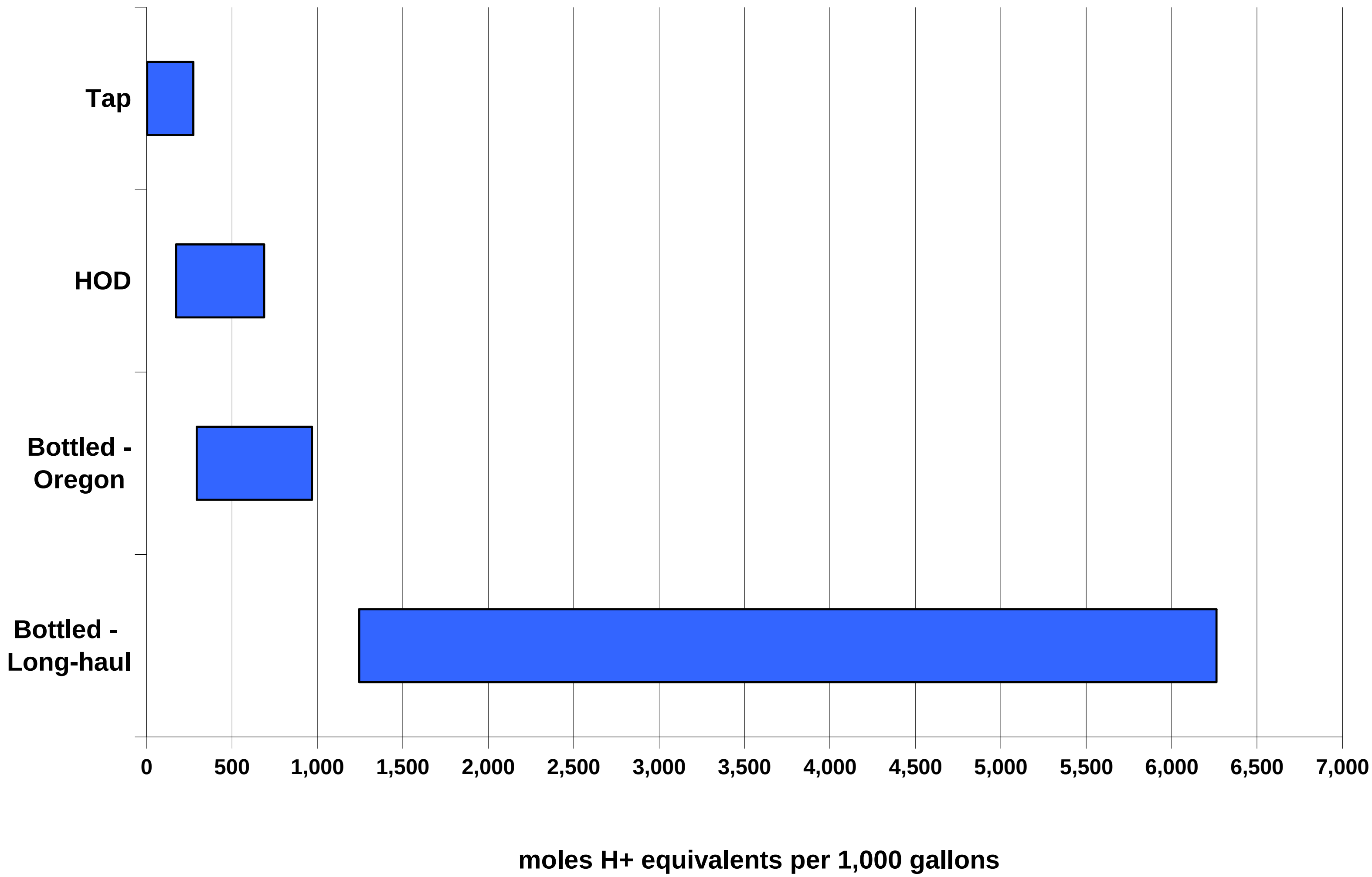


Figure 4-5. Range in Carcinogenic Potential for Subscenarios Evaluated

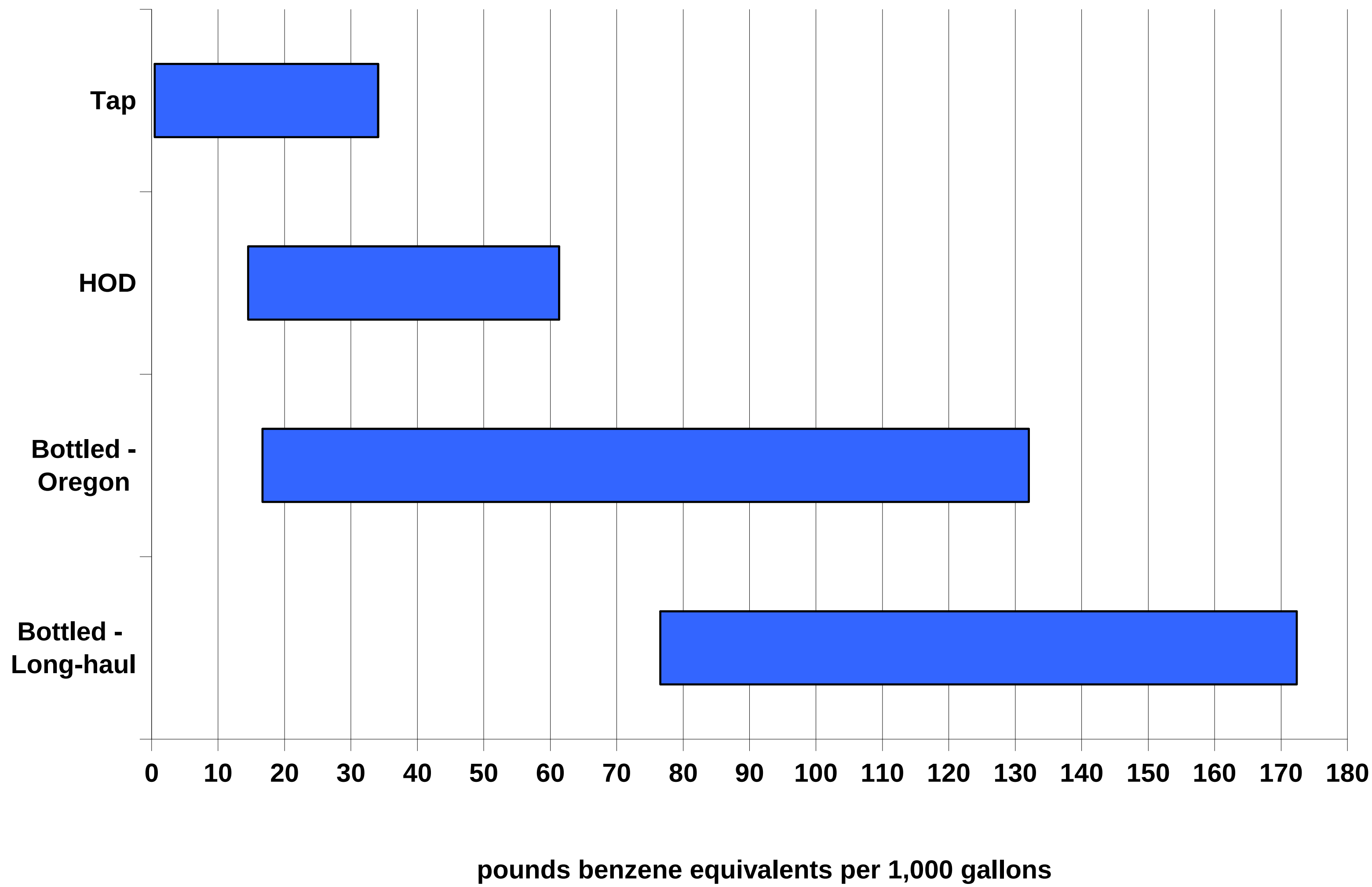


Figure 4-6. Range in Ecotoxicity Potential for Subscenarios Evaluated

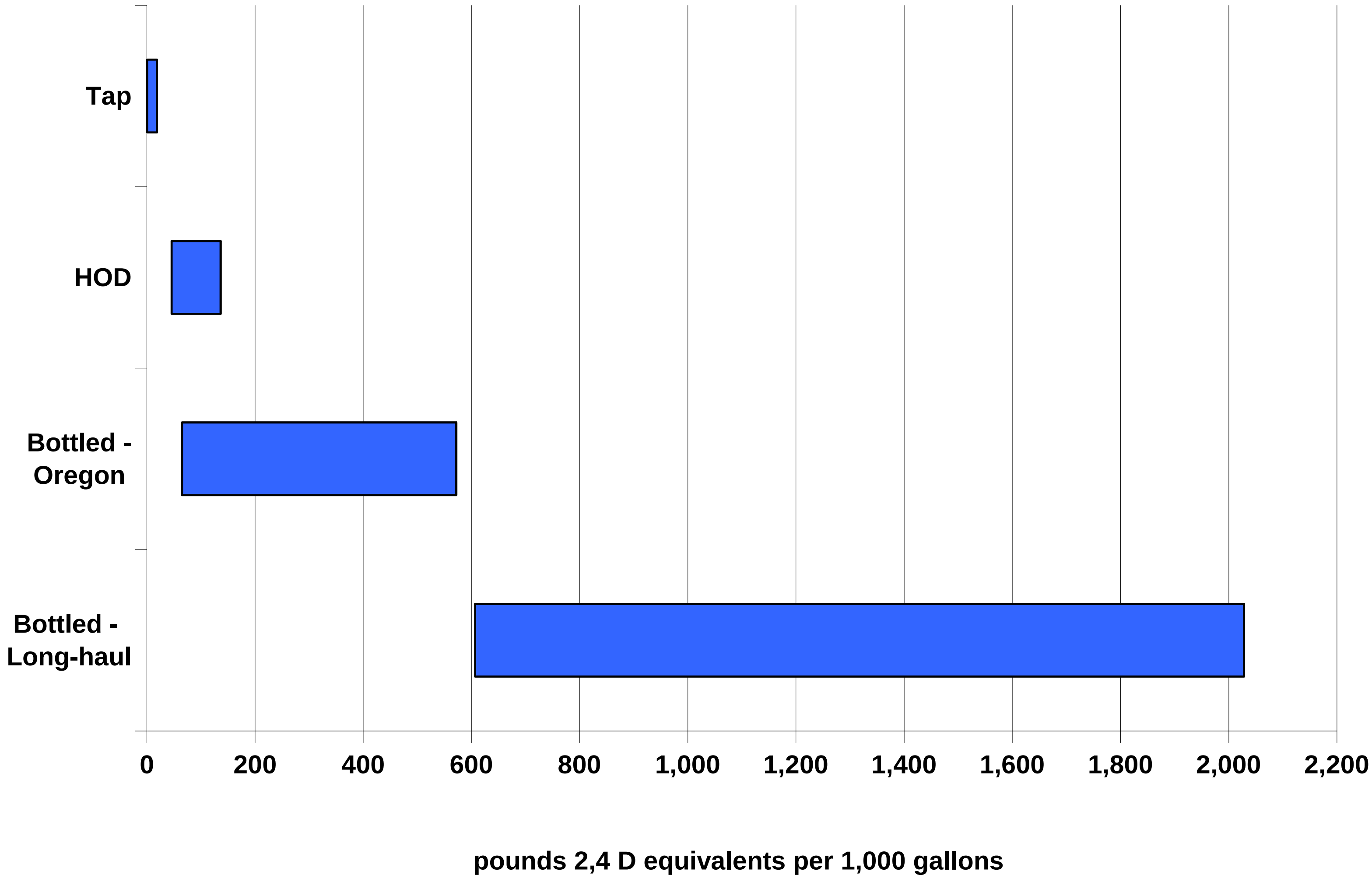


Figure 4-7. Range in Eutrophication Potential for Subscenarios Evaluated

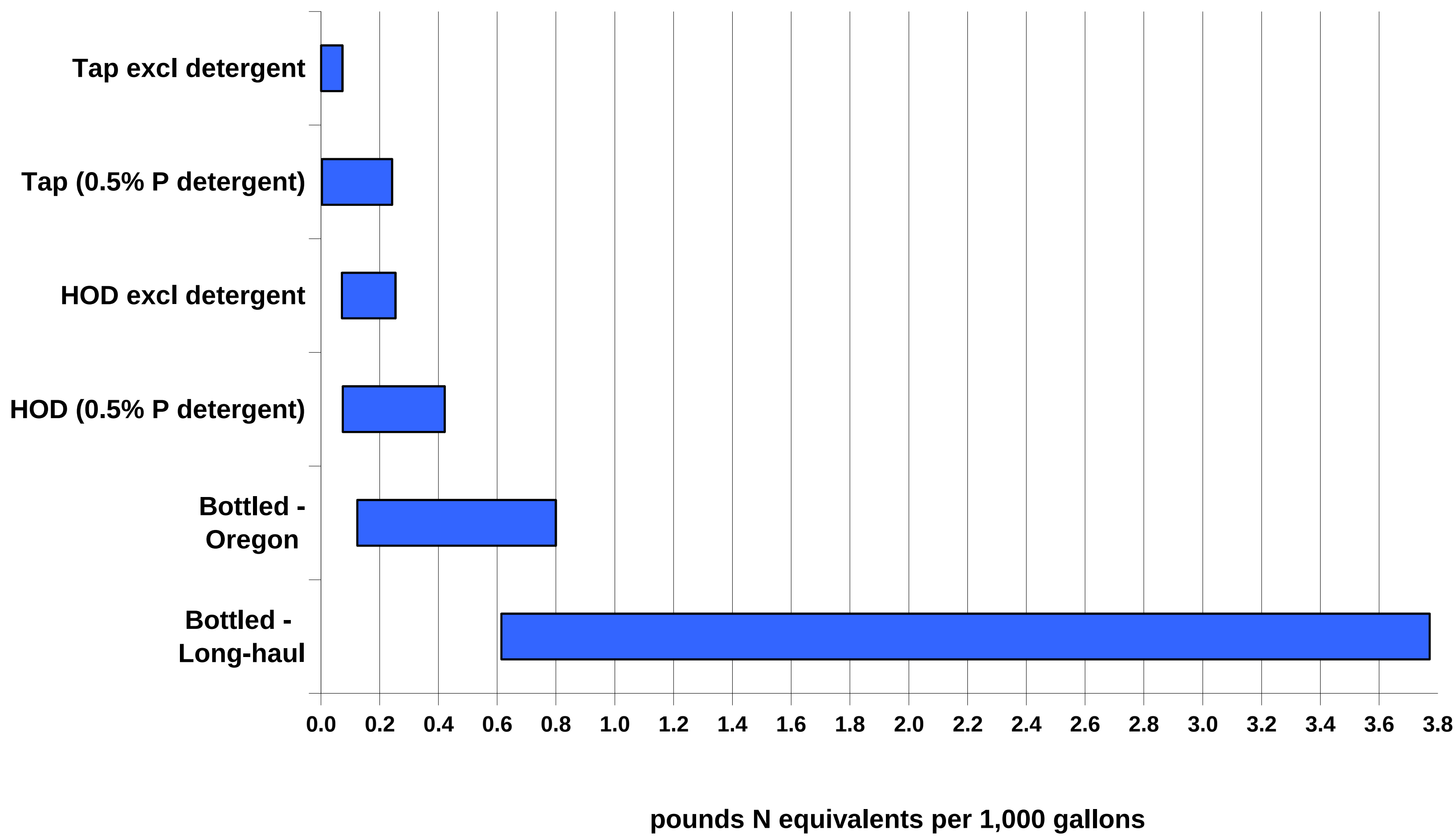


Figure 4-8. Range in Global Warming Potential for Subscenarios Evaluated

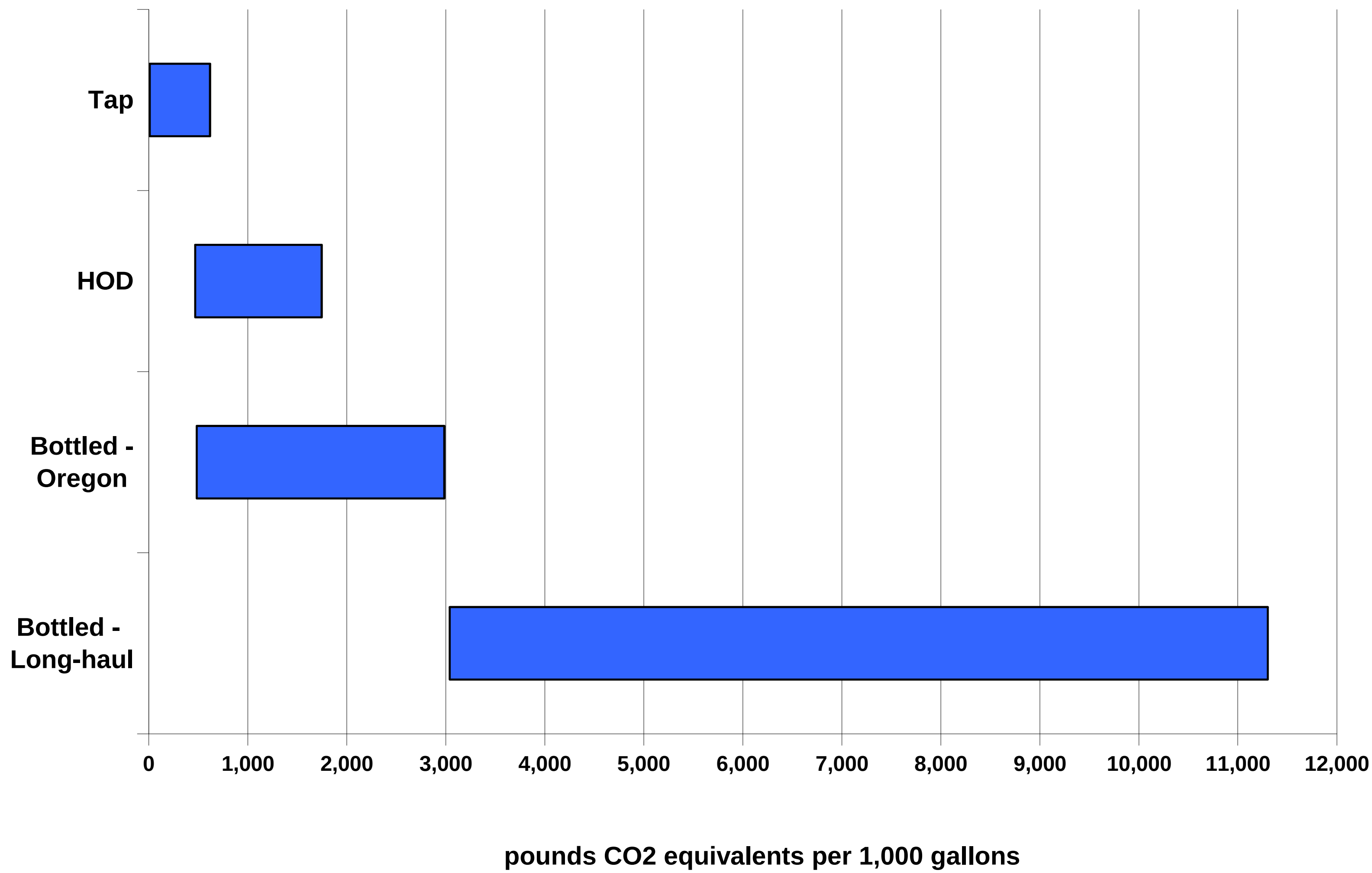


Figure 4-9. Range in Non-carcinogenic Potential for Subscenarios Evaluated

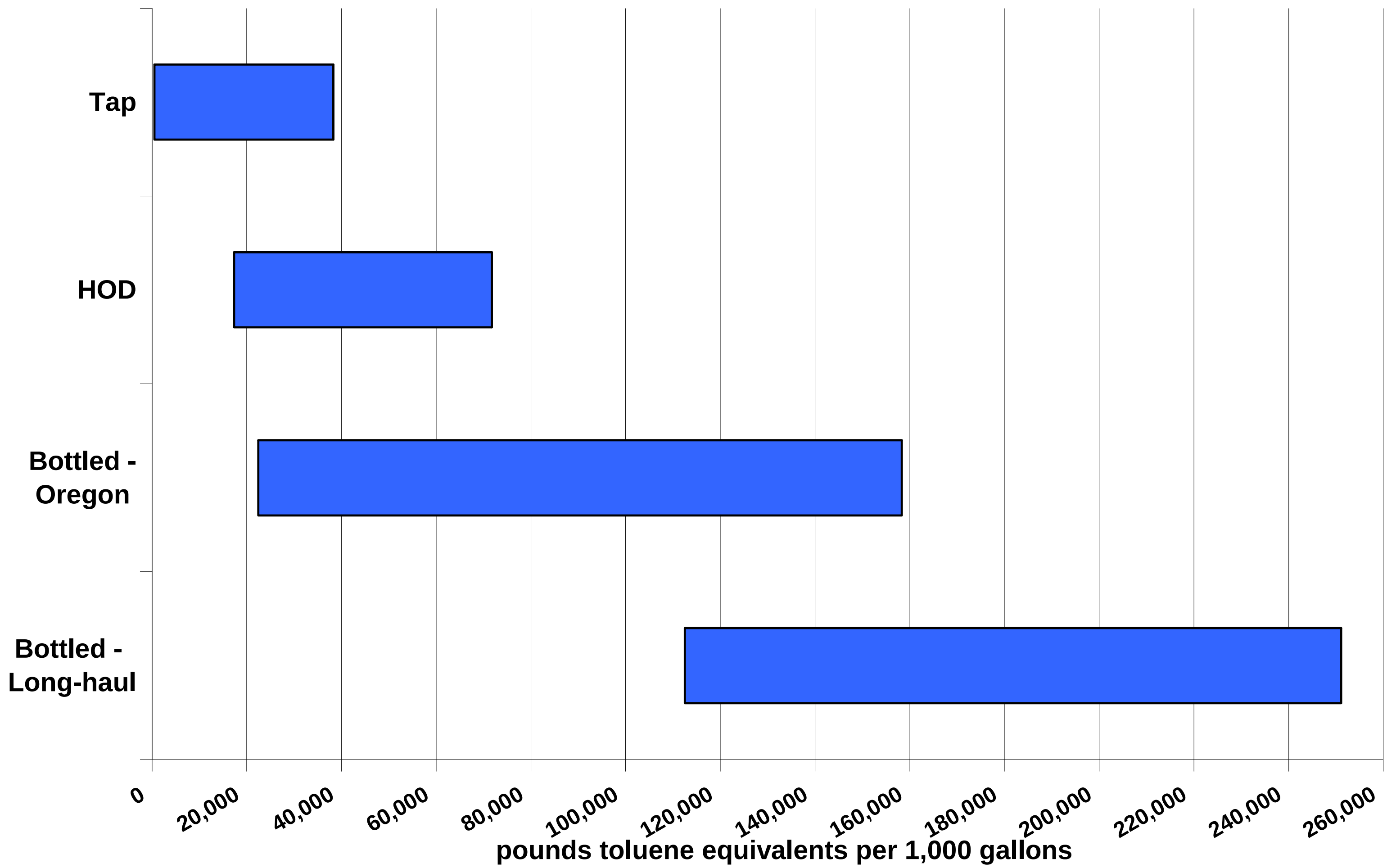


Figure 4-10. Range in Ozone Depletion Potential for Subscenarios Evaluated

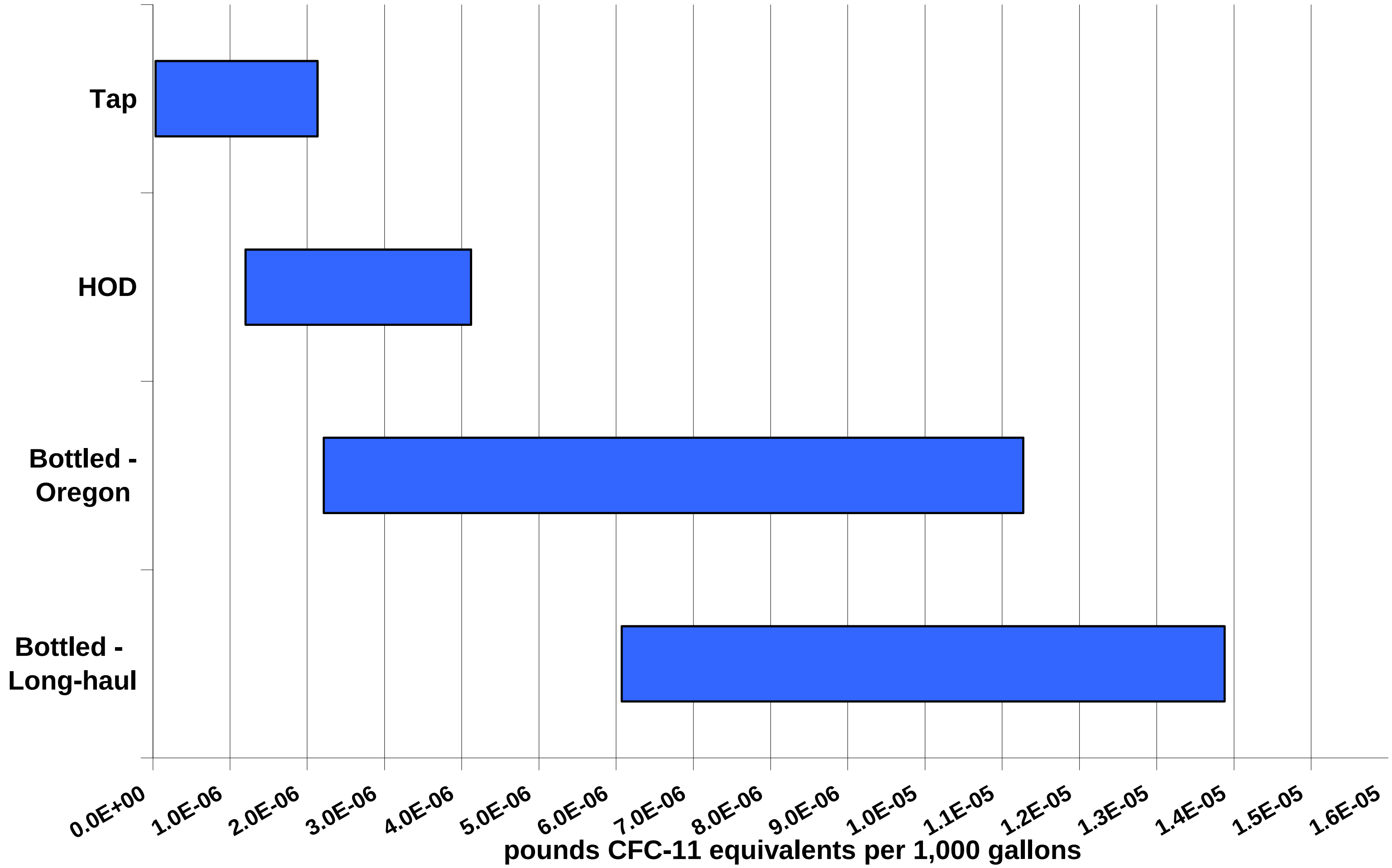


Figure 4-11. Range in Respiratory Effects Potential for Subscenarios Evaluated

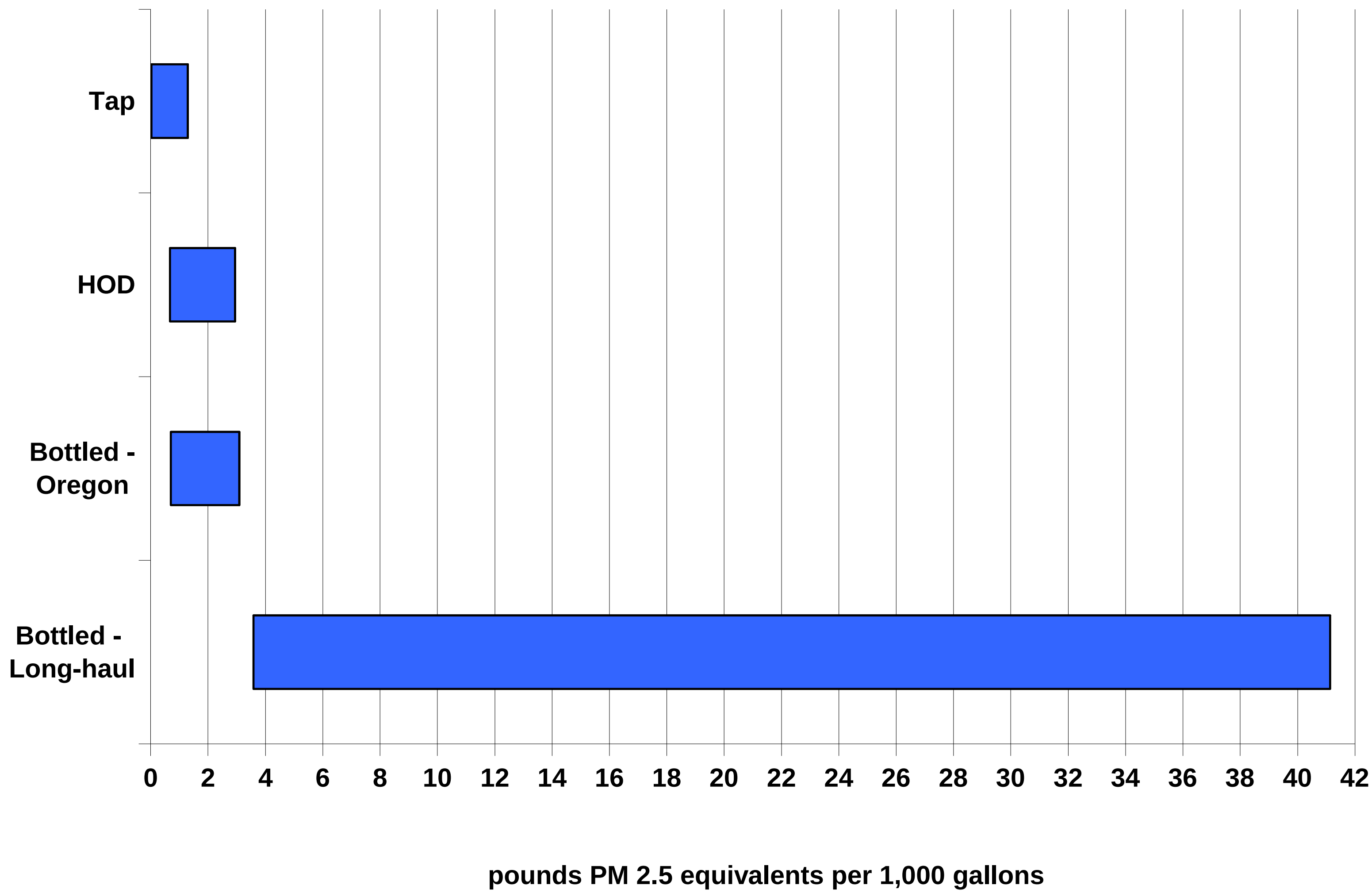
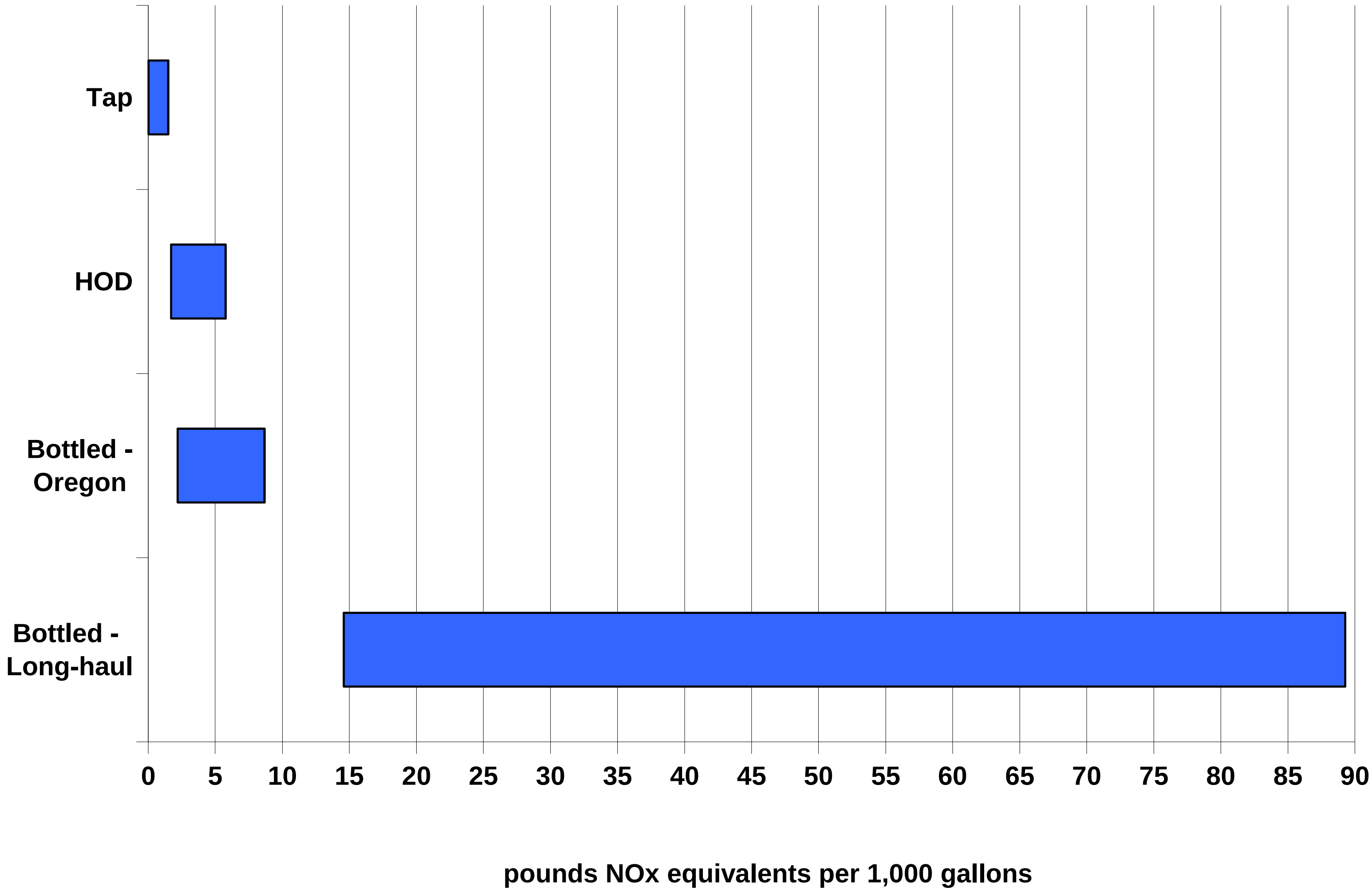


Figure 4-12. Range in Smog Potential for Subscenarios Evaluated



APPENDIX 1

CONTRIBUTION ANALYSIS FOR ADDITIONAL DRINKING WATER SCENARIOS

INTRODUCTION

This appendix presents contribution analysis results that were run in the original draft LCI. The results of the contribution analysis were used to identify parameters that made large contributions to the results for each drinking water system, to provide a basis for selecting the 48 subscenarios to be analyzed in the full LCA.

The results in this appendix are copied directly from the draft report. It should be noted that some adjustments were made to the LCI model after these draft results were run, so results in this appendix may not correspond exactly to results for similar subscenarios presented in the full report.

DRAFT LCI CONTRIBUTION ANALYSIS

In addition to the three example drinking water systems for which in-depth results tables have been presented, Figures 2-1 through 2-12 present contribution analysis figures showing how results change when individual system parameters are varied from the reference settings used for the example systems. These results will not be discussed in detail; they are presented here primarily to provide context for the selection of subscenarios to be included in the second draft report. Only those life cycle stages that contributed 1 percent or more to the total results are shown in the figures. All results are run using recycling methodology 1 (open-loop recycling), except for Figures 2-4 through 2-6 which show several scenarios analyzed using each of the three recycling methodologies, so that the influence of the recycling methodology on results can be analyzed.

On the bottled water and HOD water figures, the final two columns on each figure show the maximum spread of results based on combinations of all the minimum values analyzed and all the maximum values analyzed. It was not possible to do a min/max spread for the tap water figures because some of the minimum and maximum values were associated with different types of containers; therefore, it is not realistic to suggest that the all minimum or all maximum scenarios could be achieved with any single type of drinking container.

Table 2-7. Parameter Changes from Example Bottled Water System

	Designation used in Figures											
	Reference System = ref (PET)	wt - 10%	25% recycl cont	PLA no compost	nat, no proc	Fiji nat	bottle transp 200 mi	rinsed	store 10 mi	trip alloc 0%	1 day refrig	37% EOL recycle
Bottle material	PET			PLA								
Bottle weight	15.2 g	13.7										
PET recycled content	0%		25%									
Water source/distance	OR 50 mi				OR 130	Fiji						
Water in bottle	purified municipal				nat, no addl proc	nat, no addl proc						
Molded bottle transport	none						200					
Bottles rinsed before filling	none							yes				
Home to retail	5 miles								10			
Trip fuel use allocated to water	4%									0%		
Chilling	none										1 day in home refrig	
Recycling	62%											37%

Figure 2-1. Energy for 1000 Gallons of Bottled Water
(life cycle stages contributing <1% of total energy are not shown)

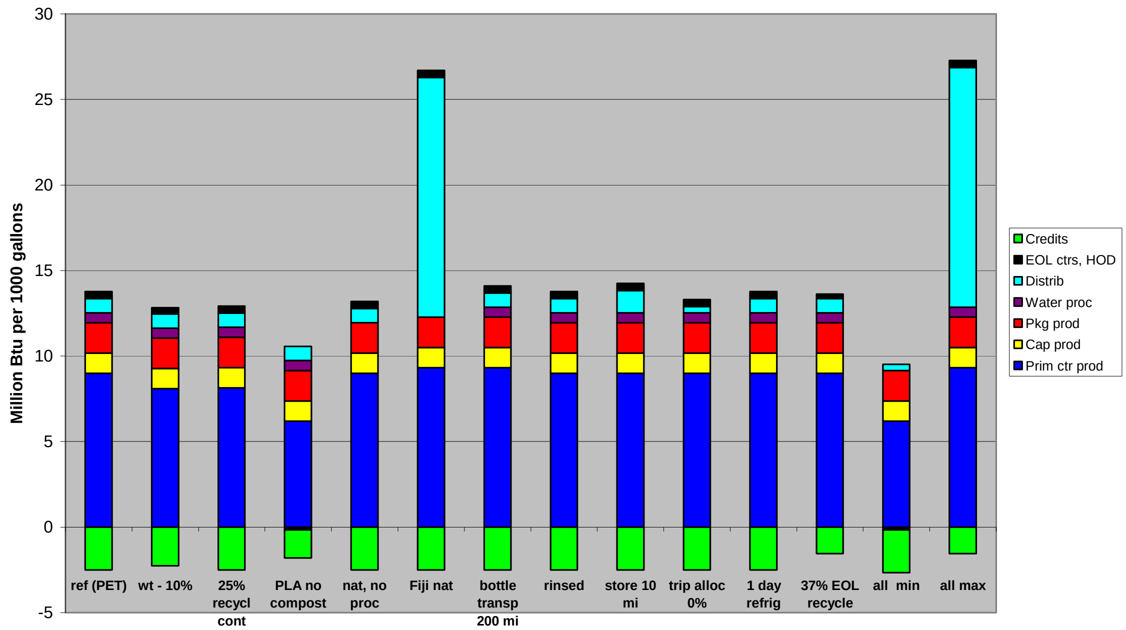


Figure 2-2. Solid Waste Weight for 1000 Gallons of Bottled Water (life cycle stages contributing <1% of total solid waste are not shown)

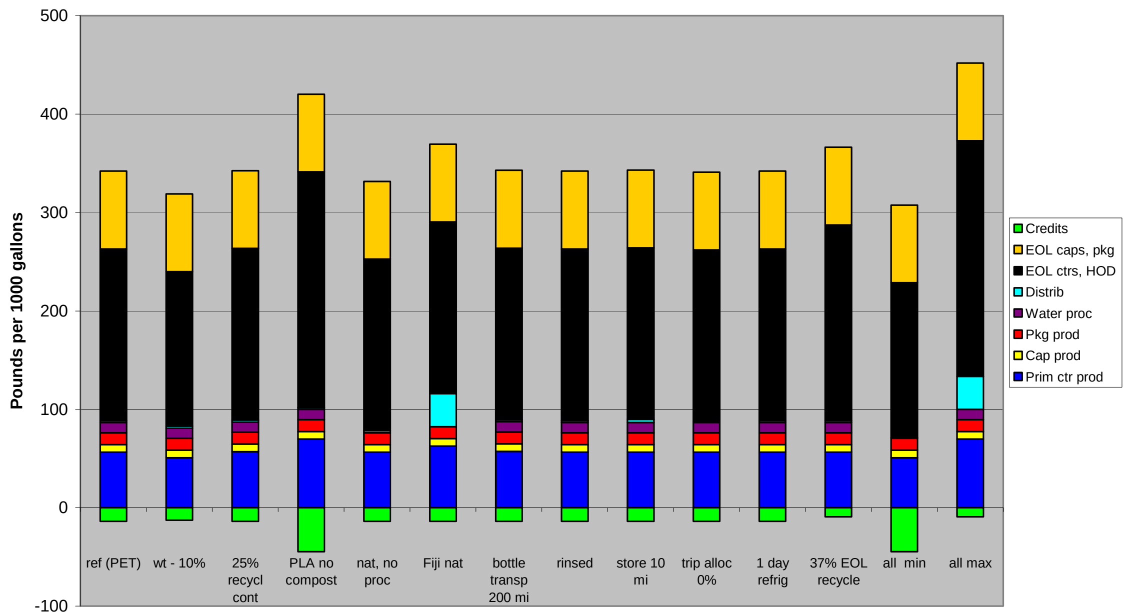
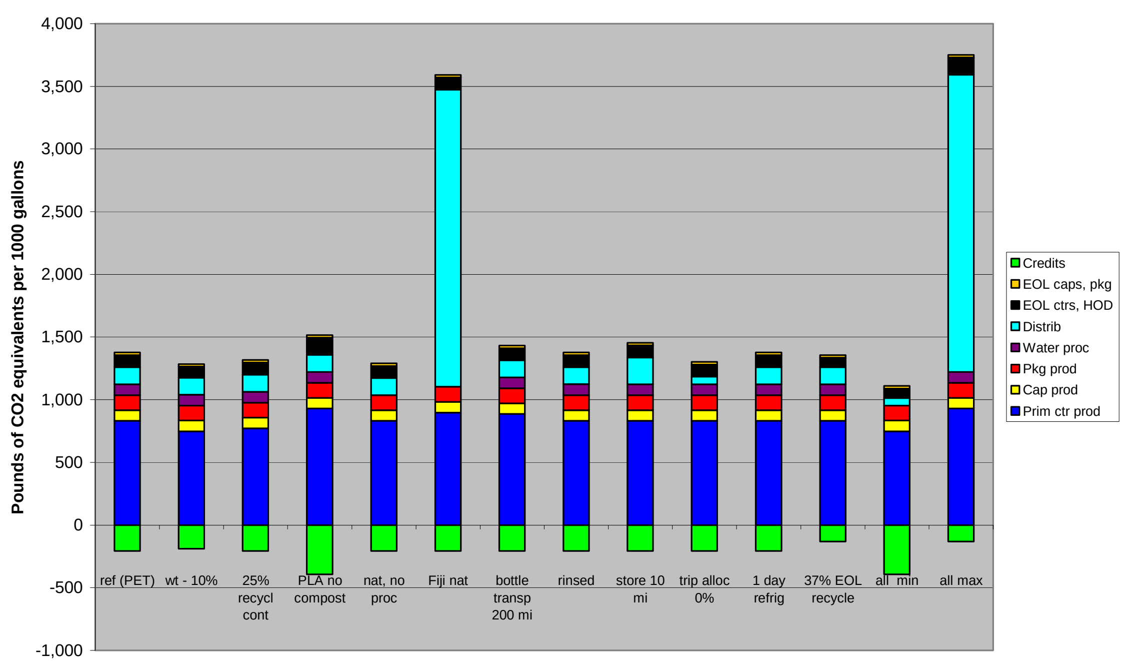


Figure 2-3. Global Warming Potential for 1000 Gallons of Bottled Water (life cycle stages contributing <1% of total global warming potential are not shown)



The following three figures show four PET bottled water scenarios evaluated for each of the three recycling methodologies. In each figure, the bottle system is the "producer" system (the system that generates material for recovery). The figures show that recycling methodology 1, the open-loop methodology, has the highest solid waste results for the producer system, since the disposal burdens for the material are shared between the systems producing and using the recycled material. The other two methodologies assign the disposal burdens to the user system. Energy, solid waste, and GWP credits are greatest for methodology 3, because this method transfers all the virgin production and disposal burdens for the recovered material to the user system.

Figure 2-4. Energy Results for Different Recycling Methodologies (life cycle stages contributing <1% of total energy are not shown)

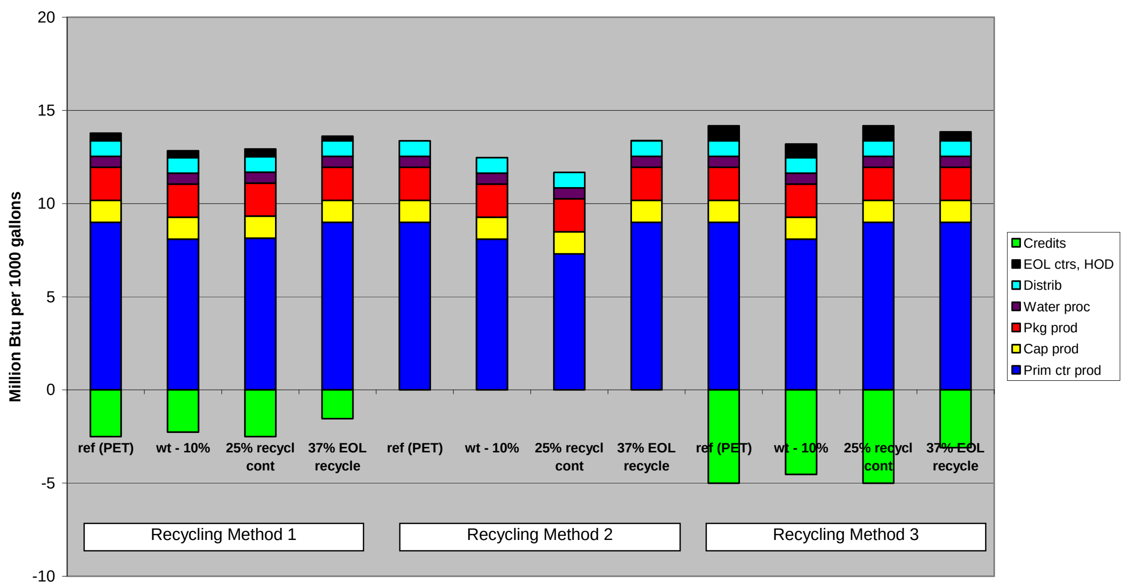


Figure 2-5. Solid Waste Weight Results for Different Recycling Methodologies
(life cycle stages contributing <1% of total solid waste are not shown)

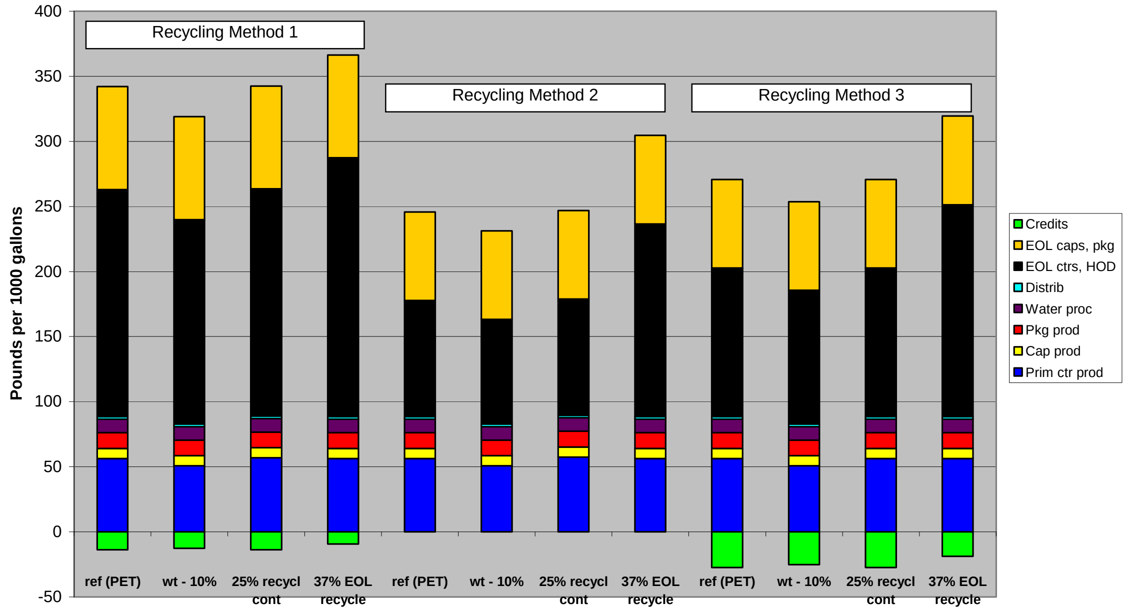


Figure 2-6. Global Warming Potential Results for Different Recycling Methodologies
(life cycle stages contributing <1% of total global warming potential are not shown)

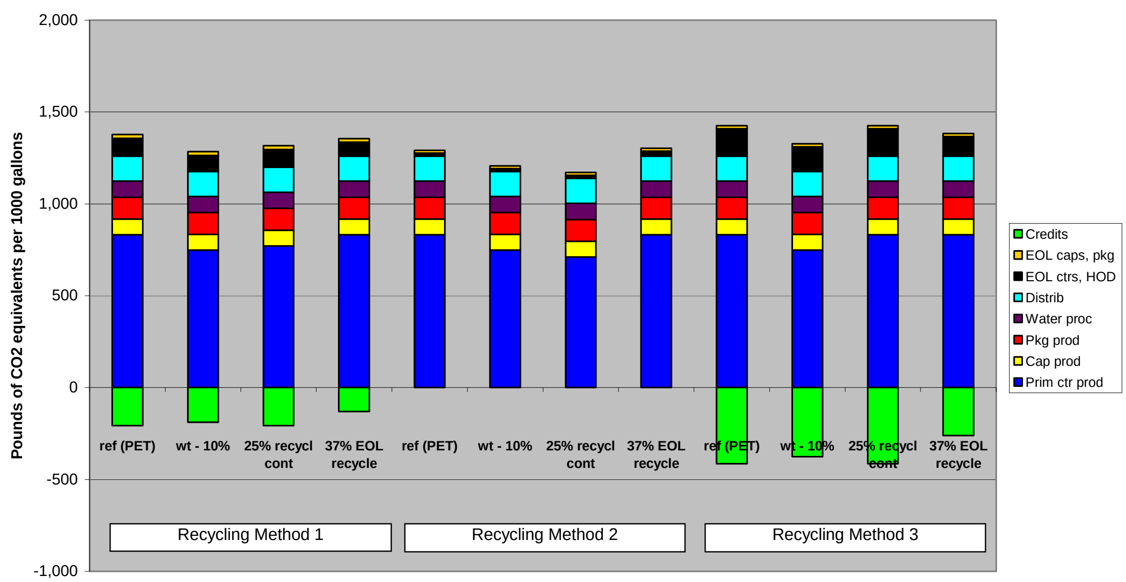
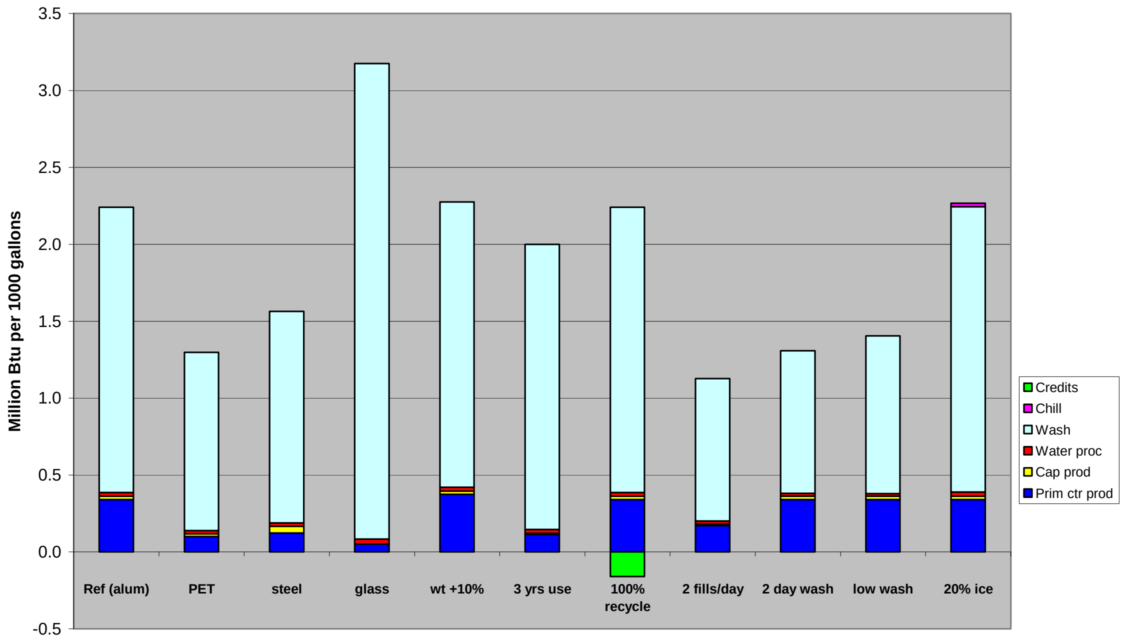


Table 2-8. Parameter Changes from Example Tap Water System

	Designation used in Figures										
	Reference = Ref (alum)	**PET**	**steel**	**glass**	**wt +10%**	**3 yrs use**	**100% recycle**	**2 fills/day**	**2 day wash**	**low wash**	**20% ice**
Reusable ctr	Aluminum	PET	Steel	Glass	Aluminum						
Container wt	100 g	104 g	227 g	184 g	110 g						
Container volume (fl oz)	20 oz	32 oz	27 oz	12 oz	20 oz						
Yrs use	1 yr					3 yrs					
Recycling when disp	0%						100%				
Container fillings/day	1							2			
Days used before washed	1 day								2		
High or low water wash	high wash									low wash	
Chilled	no										20% ice

Figure 2-7. Energy for 1000 Gallons of Tap Water Consumed from Reusable Containers (life cycle stages contributing <1% of total energy are not shown)



At first glance, the large fluctuations in results for the tap water scenarios appear somewhat random, but the majority of the variation can be understood in terms of each variable's effect on container washing, which dominates the results for all tap water scenarios. The number of drinking container washings per 1000 gallons of water consumed varies inversely with the size of the containers, the number of times the container is filled before washing, and the number of days the container is used before washing. The drinking glass system has the lowest energy use for container manufacture but has the highest washing requirements because it is smaller than the other reusable containers and requires more container washings per thousand gallons of water consumed compared to the larger containers when all are modeled as being filled once daily and washed after one filling. Similarly, doubling the daily number of container fills or washing the container every two days instead of daily reduces the washing requirements by half.

Figure 2-8. Weight of Solid Waste for 1000 Gallons of Tap Water Consumed from Reusable Containers (life cycle stages contributing <1% of total solid waste are not shown)

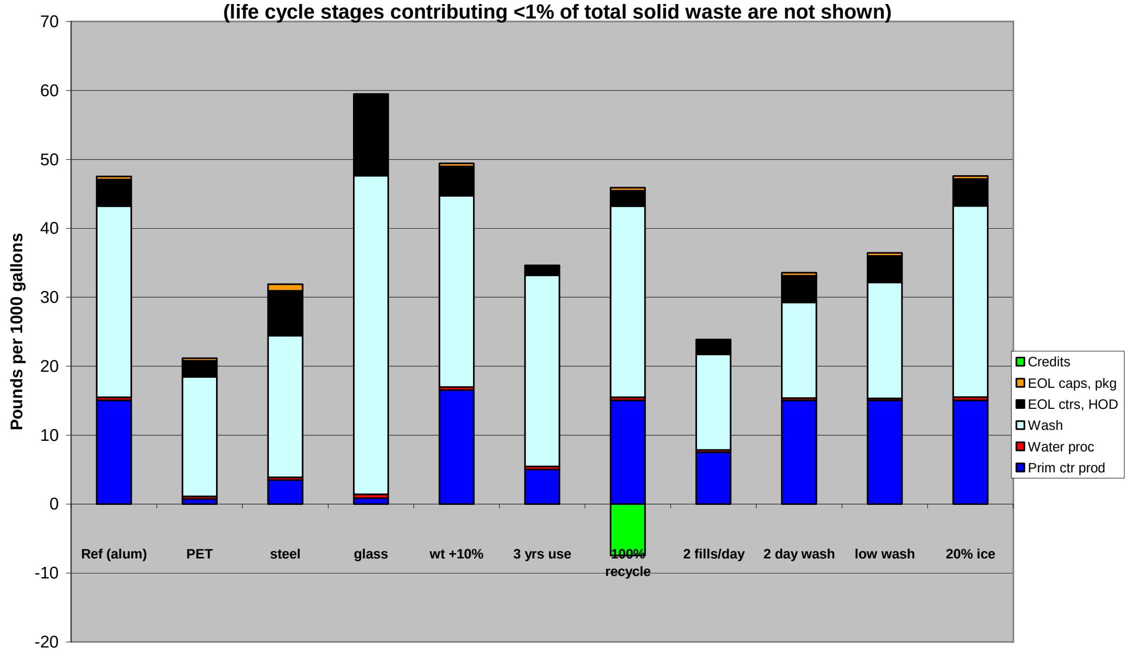


Figure 2-9. Global Warming Potential for 1000 Gallons of Tap Water Consumed from Reusable Containers (life cycle stages contributing <1% of total global warming potential are not shown)

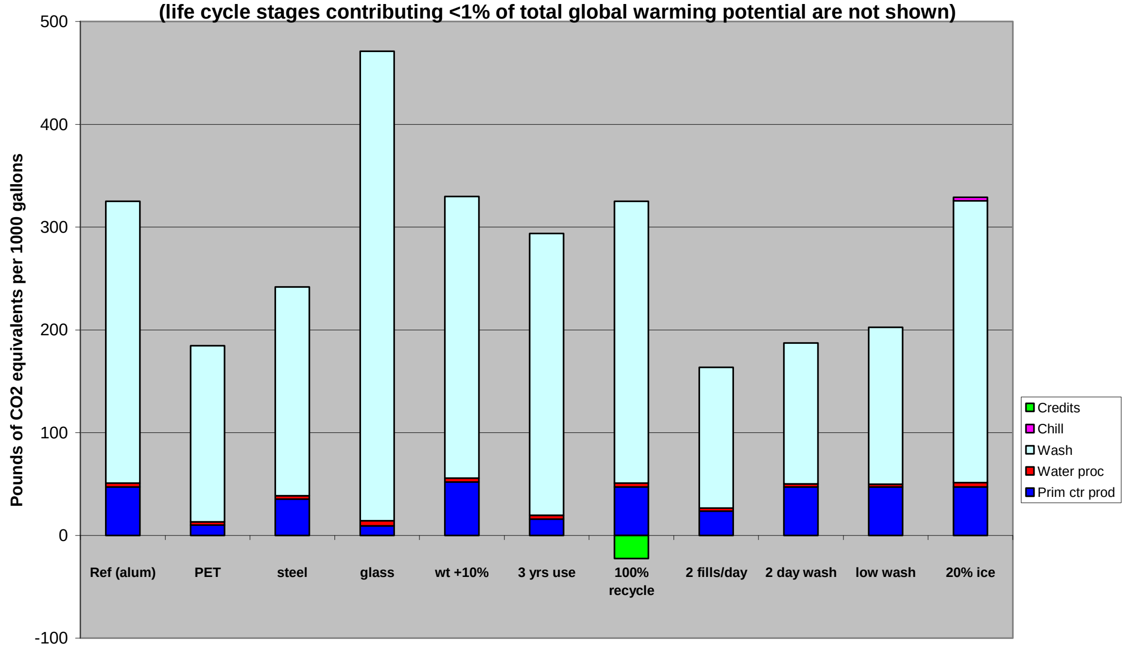
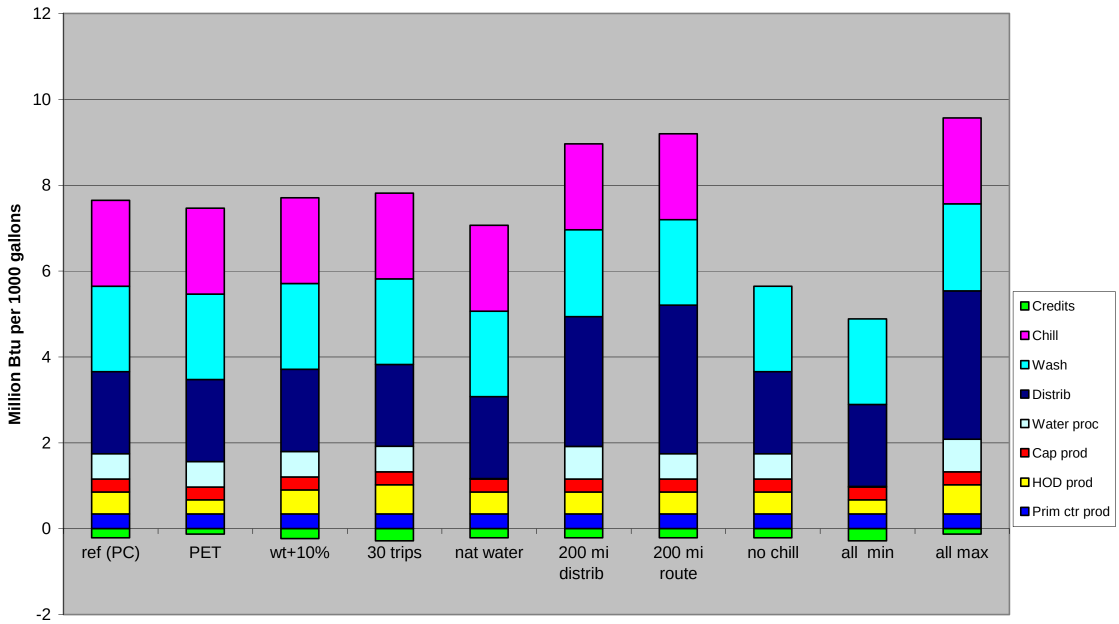


Table 2-9. Parameter Changes from Example HOD Water System

	Designation used in Figures							
	Reference = ref (PC)	**PET**	**wt + 10%**	**30 trips**	**nat water**	**200 mi distrib**	**200 mi route**	**no chill**
Reusable ctr	Aluminum							
Container wt	100 g							
Yrs use	1 yr							
Recycling when disp	0%							
Container fillings/day	1							
Days used before washed	1 day							
High or low water wash	high wash							
HOD bottle type	Polycarb	PET						
HOD bottle weight	750 g		10%					
Lifetime reuses	40			30				
Water in bottle	purified municipal				natural, no proc			
Water source/distance	OR, 50 mi					US, 200 mi		
Route miles	100						200	
Chilling	HOD chill							none

Figure 2-10. Energy for 1000 Gallons of HOD Water Consumed from Reusable Containers (life cycle stages contributing <1% of total energy are not shown)



The HOD variation figures show that the largest contributions to energy and GWP results are associated with filled container distribution, washing, and HOD chiller operation. It should be noted that the washing results shown in the figure include both HOD container washing and washing of the reusable drinking container. Washing and chilling are also the stages with the largest contributions to solid waste.

Figure 2-11. Solid Waste Weight for 1000 Gallons of HOD Water Consumed from Reusable Containers (life cycle stages contributing <1% of total solid waste are not shown)

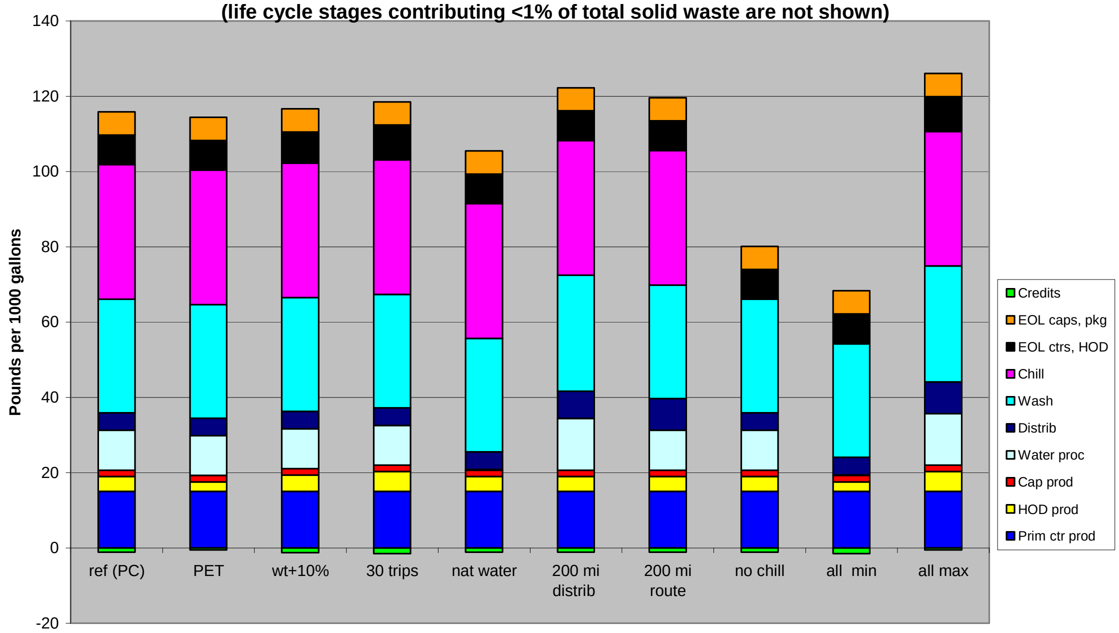
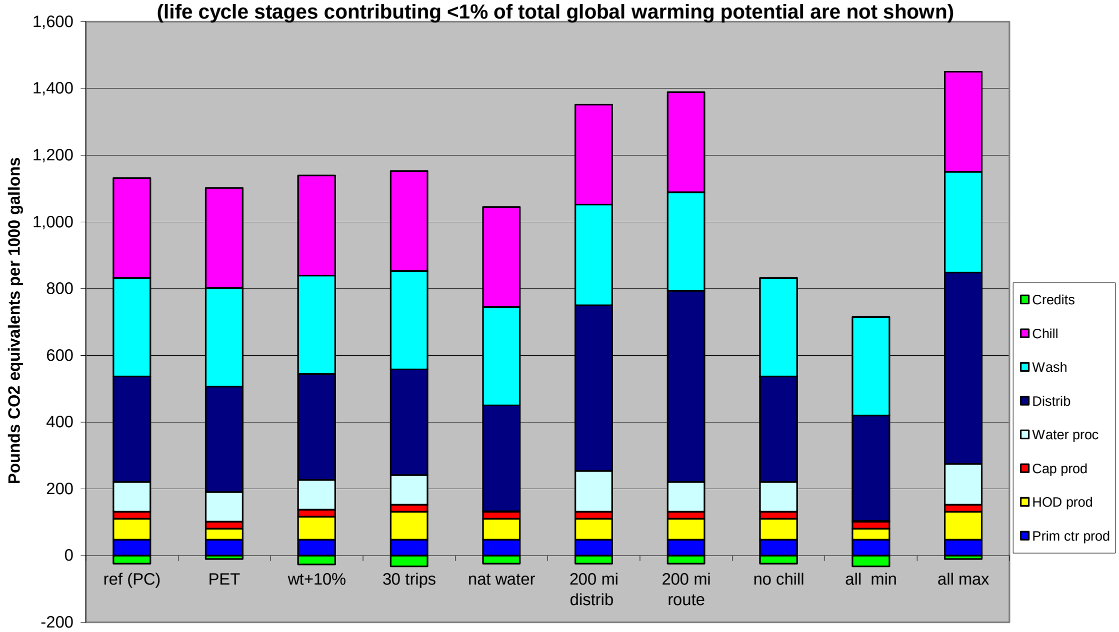


Figure 2-12. Global Warming Potential for 1000 Gallons of HOD Water Consumed from Reusable Containers (life cycle stages contributing <1% of total global warming potential are not shown)



ADDENDUM

PEER REVIEW

The following pages contain the report of the peer review panel, with ERG's responses inserted in italicized font. Qualifications of the peer review panel members are provided at the end of the addendum.

PEER REVIEW

of

LIFE CYCLE ASSESSMENT OF DRINKING WATER SYSTEMS: BOTTLED WATER, TAP WATER, and HOME/OFFICE DELIVERY SYSTEM

(Final Draft Report and Appendices)

Prepared for

THE STATE OF OREGON Department of Environmental Quality (DEQ)
and
FRANKLIN ASSOCIATES, A Division of ERG

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August 3, 2009

SUMMARY

The Oregon Department of Environmental Quality (DEQ) requested a two-stage peer review of "Life Cycle Assessment of Drinking Water Systems: Bottled Water, Tap Water, and Home/Office Delivery Water," conducted by the consulting firm of Franklin Associates, a Division of Eastern Research Group. During the first stage the peer review panel evaluated the draft life cycle inventory (LCI) report and its appendices, and provided comments to Franklin Associates. The life cycle inventory (LCI) quantified the total energy requirements, energy sources, atmospheric pollutants, waterborne pollutants, and solid waste associated with the use of 1000 gallons of bottled water, tap water, and home office delivery (HOD) water in Oregon. While bottled water was assumed to be consumed directly from the bottle, the tap water and HOD water were assumed to be dispensed into reusable drinking containers; the HOD water was also assumed to be dispensed chilled.

During the second stage the panel reviewed Franklin's final life cycle assessment (LCA) report draft and appendices. Franklin built the final LCA upon its preliminary LCI findings, while expanding the LCA to (a) address many of the panel's preliminary concerns, (b) add extensive sensitivity analyses, and (c) add a life cycle inventory assessment (LCIA) of 9 impact categories, using the EPA's TRACI methodology.

In conformance with ISO 14044:2006 Section 6.3, the panel consisted of 3 external experts independent of the study. During each stage they reviewed the draft LCA report and its appendices against the following six criteria, to ensure the analysis had been conducted in a manner consistent with ISO standards for LCA:

- Is the methodology consistent with ISO 14040/14044?
- Are the objectives, scope, and boundaries of the study clearly identified?
- Are the assumptions used clearly identified and reasonable?
- Are the sources of data clearly identified and representative?
- Is the report complete, consistent, and transparent?
- Are the conclusions appropriate based on the data and analysis?

In general, the panel feels the final report both conformed to ISO standards, as defined by the review questions above, and responded to the panel's preliminary concerns. For clarification and improvement, the panel offers the following detailed responses to these same questions.

Is the methodology consistent with ISO 14040/14044?

The methodology is generally very consistent with ISO 14040:1997 and ISO 14044:2006. Objectives, scope, and boundaries are identified, as well as most assumptions.

One requirement of ISO 14044:2006 is the clear definition of the study goal. According to Section 4.2.2 that goal "shall…unambiguously" state "the intended application; the reasons for carrying out the study; the intended audience…whether the results are intended to be used in comparative assertions intended to be disclosed to the public." In the preliminary review, it was noted that and that it was not clear whether comparative assertions were planned. It was also noted that ISO 14044:2006 required the following additional information be included in a report with a "comparative assertion intended to be disclosed to the public" (Section 5.3.1):

- Detailed sensitivity analyses in the life cycle interpretation phase.
- A statement that the LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks (Section 5.2.e.8).
- A statement that "ISO 14044 does not specify any specific methodology or support the underlying value-choices used to group the impact categories." (Section 5.3.2.e)
- A statement that "The value-choices and judgments within the grouping procedures are the sole responsibilities of the commissioner of the study (e.g. government, community, organization, etc.)".

In its final report Franklin has addressed all of these issues.

Are the objectives, scope, and boundaries of the study clearly identified?

In general, objectives, scope, and boundaries are very clearly identified.

- One issue that has gained prominence, since the preliminary review was performed, is the carbon emission implications of direct and indirect land use. Recent guidance from the US Environmental Protection Agency (EPA) regarding life cycle assessments for renewable fuels (http://epa.gov/otaq/renewablefuels/420f09024.htm) indicates that changes in carbon storage in lands used to grow crops should be included in life cycle greenhouse gas assessments. Sample LCAs from the EPA for renewable fuels indicate that these land use changes can lead to significant changes in greenhouse gas emission assessments.

  Direct and indirect land use changes have not been incorporated into the PLA analyses in this report. This should be made clear in the discussion of system boundaries.

  Response: *A statement has been added to the Scope and Boundaries section as suggested.*

- A statement should be included that the scope does not include disposable drinking vessels for the tap water or HOD cases, but only washable/refillable containers. Further, a statement should be made that the scope does not include using personal bottles sold filled as reusable drinking vessels.

Response: *Statements have been added to the Scope and Boundaries section as suggested.*

- The LCA boundaries have been properly expanded with sensitivity tests. Franklin correctly points out one study case, PET bottles, contains many subsets which create a range of answers and that other options are not so thoroughly described with as many subsets.

  The sensitivity choices in the first LCI draft seemed reasonable. The final LCA draft provides multiple scenarios which generally span the likely cases. The Table 2.6 sensitivity analysis is useful in determining relative impacts.

- The analysis shows the largest influence in burdens for tap water is washing. The authors include cases for washing in full and half full machines; however, individual drinking vessels are likely to be hand-washed. A section is needed to show whether washing and rinsing by hand (water amounts, temperature and detergent use) either is less burdensome or more burdensome than machine washing.

  Response: *The basis for assuming that drinking containers are likely to be hand-washed is unclear. Most U.S. homes have dishwashers, and it is expected that the majority of dishwashing is done by machine rather than hand-washing. Variability in consumer practices is much greater for hand washing than for dishwashing operation, so that individual consumer practices determine whether hand-washing is more or less burdensome than machine washing. The California Energy Commission Consumer Energy website for Dishwashers states the following: "According to research, a load of dishes cleaned in a dishwasher requires 37 percent less water than washing dishes by hand. If you fill the wash and rinse basins of your sink instead of just letting the water run, however, you will use half as much water as the normal dishwasher load."[39] Although the specific research supporting this statement was not identified by CEC, several other internet sites discussing hand-washing versus automatic dishwashing refer to research by the University of Bonn, whose Household Technology research website has multiple reports on dishwashing[40], including detailed research on consumer hand-washing practices, which are found to be highly variable from person to person, and a comparison of automatic and hand-washing energy and water use, which shows lower burdens for machine washing.[41] A paragraph has been added to the Scope and Boundaries section addressing hand vs. machine washing.*

- The issue of water usage is an important omitted subject. The authors do express regret that there are no LCA conventions on unit water usage (process water, cooling

[39] http://www.consumerenergycenter.org/home/appliances/dishwashers.html

[40] http://www.landtechnik.uni-bonn.de/ifl_research/ifl_research_projects.php?sec=HT

[41] http://www.landtechnik.uni-bonn.de/ifl_research/ht_10/HuW2_2007washing_up_part2.pdf

water, water evaporated, etc.). In the appendices process water is included for some materials, but not all.

Are the assumptions used clearly identified and reasonable?

Generally, the assumptions are clearly identified. However, the panel questions the reasonability of some.

- **Packaging**

Considering the significant impact which container weight has on LCI results, the methodology used to select the 13.3-gram bottled water PET container weight studied is of great concern. Table B-1a (Appendix B) only lists 8 PET bottled water container weights which were averaged to produce this number.

- 6 values appear to be weights from single bottle purchases in the Kansas City area of a variety of different brands, such as Aquafina and Purelife. Five were measured in 2009 and a sixth in 2007.
- A value quoted in the Wall Street Journal.
- A value provided by Oregon DEQ.

Response: *The above summary of the bottle weight data is not correct. The weight data consist of three individual bottle samples obtained in Kansas City and weighed by ERG staff, one bottle sample obtained in Oregon and weighed by DEQ staff, five current average bottle weights from the largest U.S. bottlers as cited in the Wall Street Journal in March 2009, and one future bottle lightweighting scenario cited in the Wall Street Journal article.*

The 8 values ranged from 10.1g to 20.1g, with the highest value (20.1) being provided by the Oregon DEQ. Considering the extreme importance of container weight in the analysis, a much more comprehensive container sampling plan appears to be warranted. Further, with the broad range of weights listed in Table B-1a, a much greater than +/- 10% variability should have been explored in the sensitivity analyses listed in Table 2-6. Also, the large difference between the 20.1g Oregon DEQ weight and the 13.3g study weight needs to be explained.

Response: *The scope of the analysis did not include extensive sampling of bottle weights. We believe that the data cited in the Wall Street Journal article provide a good representation of the weights of the majority of the bottles currently in the marketplace. The Oregon sample was a sample from a small Oregon spring water bottler; the 13.3 g weight used in the study is the average bottle weight including the bottle weights used by large national bottlers that would account for a large share of bottled water sold in Oregon.*

Table B-1a (Appendix B), footnote 3 says, “Glass bottle weight is the average of two samples obtained and weighed by Franklin Associates in 2009.” First, basing the glass container weight used in the LCI on only 2 data points is of serious concern, considering retail bottle weights vary due to manufacturer light-weighting, manufacturing plant upgrades, and even variability in the manufacturing process at a single plant. Second, this information combined with information from Footnote 2 at the bottom of page B-1 is even more disturbing. Footnote 2 reads, "One glass bottle of carbonated water had an aluminum cap; however, this analysis does not include carbonated water, so the glass bottle closure was modeled based on the PP closure that was used on a glass bottle of non-carbonated bottled water." From Footnote 2 it appears the weights of a bottle holding carbonated water and a bottle of non-carbonated water were averaged to obtain the glass bottle weight used in the analysis. This analysis focused on non-carbonated water. To withstand the pressure of carbonation, the carbonated water bottle was probably significantly heavier.

Response: *The small number of glass bottle samples was due to the difficulty in finding bottled water packaged in glass. Although PET bottles used for carbonated beverages need to be thicker (and heavier) than PET bottles for water, the same does not appear to be true of glass. The weight of glass per fluid ounce of water packaged was very similar for the glass bottles containing carbonated and non-carbonated water. The weight of glass per ounce of water was actually slightly higher for the bottle containing non-carbonated water.*

The final report also describes an impact assessment based on the life cycle inventory information, and for two of the impact categories, carcinogenic and non-carcinogenic potential, packaging plays a role. As noted on pages 3-6 and 3-12 (below), large shares of the impact in these categories are due to the role of dioxins associated with the production of secondary packaging.

- "The TRACI characterization factor table (at the end of this chapter) shows that dioxin emissions have by far the greatest impact factors compared to all other substances contributing to carcinogenic potential in this analysis." (Page 3-6)
- "The non-carcinogenic characterization factor for dioxin emissions is orders of magnitudes greater than the characterization factors for all other emissions contributing to this category; therefore the results are driven by systems' use of wood, coal, and residual and distillate oil as process fuels and fuels for the production of electricity." (Page 3-12)

Although it is not discussed in the report, assigning dioxin emissions to corrugated products must be due to an allocation among multiple paper products. Chlorine is needed to make dioxin; it is not clear that it is appropriate to assign chlorinated emissions to non-bleached paper products. This issue should be discussed in the final report. Either there are dioxin emissions from unbleached paperboard, or the text needs correction.

Response: *The dioxin emissions for corrugated product manufacture are not associated with bleaching. The EPA's Compilation of Air Pollutant Emission Factors (AP-42) reports dioxin emissions for the combustion of wood wastes, which are used for process energy at mills producing both bleached and unbleached paperboard.*

The aluminum used for the refillable bottles is listed as virgin aluminum on charts, but not in text. This assumption is important for determining the burden of making the bottles, but decreases as the number of uses increase. A statement in the text would be useful.

Response: *The aluminum bottle is described as virgin aluminum in the Systems Studied section, and "virgin" has been added in several places to describe the bottle..*

Transportation assumption explanations are needed for recycled materials.

Response: *The transportation modes and distances for recycled materials are described in Appendix J.*

Why were no recycled content options explored for the PET HOD bottles? Since these are closed loop systems, they are ideal candidates to recover material that doesn't need to be sorted and very probably isn't contaminated. However, due to the high trippage rates of these containers, any recycling content savings would probably have little impact on the LCI results.

Response: *Interviews with HOD bottlers indicated that recycled content is not currently used in HOD bottles.*

A primary finding from the preliminary study is that the life cycle energy, solid waste and greenhouse gas inventories for the bottled water system are dominated by contributions from the bottle. As a result, the panel recommended a sensitivity analysis be included for the delivery of the bottled water to the consumer in differently sized containers. This has been done in the final LCA report.

- **Functional unit**

The functional unit chosen for use in the study is 1000 gallons of water, delivered in a portable container, to a consumer. However, the quality of the water delivered is not uniform in the three product systems. Specifically, for the tap water system it is not clear why the authors did not include the use of home filters or home reverse osmosis systems in the analyses, to make this system more consistent in water quality with the other two water delivery systems. While it is clear that the study authors have limited information in assessing the purification systems used in the water processing and bottling operations, some sensitivity analyses could be performed dealing with water quality. Specifically, data presented in Appendices B and F (pages B-6, F-1 and F-2) for bottled water filtration and reverse osmosis, indicate that no burdens were assigned to water filtration and only electricity burdens were associated with reverse osmosis. A sensitivity analysis could be performed assessing the implications of assigning these same treatment burdens to tap water.

Response: *Additional at-home treatment of tap water was not included in the scope of the analysis. Equivalence of the drinking water delivered by the various systems is* *based on water that meets regulatory standards for cleanliness, as described in the Functional Unit section of the report. A statement about the exclusion of home treatment of tap water has been added to the Scope and Boundaries section.*

It is implied that all options provide bacterially safe water in containers. However, the study allows for consumer choice to wash personal drinking vessels after every use or infrequently. For the same level of bacterial safety, the emphasis should be on the tap and HOD drinking vessels being fresh and unused since the last washing.

Response: *Because the tap and HOD water are sanitized to meet regulatory standards, any bacterial contamination would come from use of the drinking container (i.e., bacteria from the user's mouth contact with the container), not from the tap or HOD water put into the container. As shown in Table 2-9, the majority of the reusable drinking container scenarios are based on washing the container after each use.*

In response to earlier questions from the panel, Franklin has included the option of chilled water for all delivery systems. In the section titled "Functional Unit" the authors do note that the aesthetic quality of the different waters may be different. LCA's do not generally include quality as a measure, and there will be a difference between chlorinated tap water and chlorine-absent packaged water.

It is assumed that with transportable consumption containers the fixed sources (tap and HOD) are as convenient as bottled water.

- **Water Delivery**

As noted in the panel's preliminary review, a primary LCI finding was that the life cycle energy, solid waste and greenhouse gas inventories for the HOD water system are dominated by contributions from the delivery. Given this finding, it is important that comparative assertions are based on a consistent handling of water delivery. A detailed description of the retail to home delivery mechanism was provided for the bottled water system; however, it was not clear from the draft report how tap water delivery was handled. Some of the issues were resolved in Appendix E of the final report, which describes well water pumping requirements. However, it was not clear how municipal pumping requirements were addressed. These pumping requirements may be significant in some localities. For example, in California aqueduct pumping is done over long distances. The final report should clarify the distances over which tap water is presumed to be pumped in Oregon.

Response: *Water processing and pumping data were derived from a national database (AWWA), which included energy for both processing and distribution but did not describe pumping distances or report data at a level of detail where pumping energy for processing could be separated from pumping energy for distribution.*

In addition, the report would also benefit from more detailed descriptions, and perhaps sensitivity analyses, regarding the importance of water delivery capital infrastructure for the three product systems.

Response: *As described in the Methodology chapter, capital equipment and infrastructure are not included in the scope of the analysis. The impacts of water delivery infrastructure would be very small when allocated to a functional unit of 1,000 gallons of drinking water.*

Page 1-8, paragraph 1 states, "The 25-item purchase is an estimate by the LCA practitioner, since no data are readily available for consumer purchasing patterns on an individual shopping trip basis." However, many retailers, including major supermarket chains, are now tracking consumer buying data though customer card systems, frequently giving customer discounts as an incentive to obtain and use the card. Consumer purchasing patterns should be available through these retailers.

Response: *Retail chains are increasingly tracking consumer purchasing patterns; however, these data are generally for private internal use by the retailer. We were unable to find any published data on consumer purchasing patterns that were developed from retailer tracking programs.*

- **Container Washing**

As dishwasher loading is critical to the burdens for the tap water system, an examination of the full load is needed. The 110 bottles per dishwasher load statement needs a statement of experimental confirmation. Certainly, 110 bottles per load is an upper limit value. (Table I-2 and 3-9)

Response: *The 110 bottle full loading was used to allocate dishwasher operation to bottle washings, with a single bottle occupying 1/110 of a full dishwasher load (not washing 110 bottles at a time). The 110 bottle/load maximum loading was not experimentally verified by fully loading a dishwasher with drinking containers, but was estimated two ways: (1) estimated based on information about the number of place settings and serving pieces per load that the Department of Energy specifies for dishwasher testing and ERG assumptions about the comparable number of drinking containers, and (2) estimated based on the interior dimensions of a dishwasher and the diameter of a drinking container. For example, typical dishwasher dimensions are 24 inches wide x 24 inches deep, and personal drinking containers have a diameter of 3 inches or less. The maximum number of 3-inch diameter drinking containers that would fit in a rectangular array in a 2-rack dishwasher would be* $(24 \times 24)in^2$ *per rack/*$(3 \times 3)in^2$ *per container x 2 racks = 128 containers per full dishwasher load.*

Appendix I details the HOD container washing process on page I-6; however, it's unclear whether final rinse cycle water is recycled into the wash cycles, as is done in bottle washers.

Response: *The HOD processor did not provide a detailed description of water circulation in the washing process; however, the effects of water recycling would be reflected in the energy and water use that were reported. Based on the low net volume of water used per bottle, it is likely that the water is recycled.*

- **Other Assumptions**

The preliminary LCI review indicated that the report should address the following questions:

- What assumptions were made about washing temperatures and other washing assumptions for the reusable containers?
- Would the use of updated GWP factors (see page 2-12) have a significant impact on results?

The first of these issues has been addressed in the LCA; however, the report still uses 1996 GWP factors (page 2-17).

Response: *The text on page 2-17 has been revised to clarify that the 1996 GWP factors were used to develop the example GWP results shown in Tables 2-6 through 2-8. GWP impacts in the full report are calculated using factors in the TRACI LCIA methodology, shown in Table 3-11. Since over 90 percent of total GWP for all scenarios are from carbon dioxide, which always has a reference GWP of 1, the use of updated GWP factors for other emissions would not have a significant impact on results.*

In addition, the following assumptions should be addressed or clarified:

- As described on page 1-7, when co-products of heat, steam or fuel are produced, an energy credit is given. It is not clear whether this credit includes pre-combustion energy.

  Response: *For co-produced energy that is exported from the boundaries of the system, the Btu value of the exported energy is subtracted from the total energy requirements for the process where it is produced. No pre-combustion energy is included in the credit.*

- Would different assumptions regarding co-product allocation between corn starch and other corn co-products (page 1-7) lead to significant changes in the calculations?

  Response: *Because the data set for production of PLA is a "black box" with inputs of corn and output of PLA, it was not possible to investigate the effect of different co-product allocations for processes within the boundaries of the data set.*

- The methods used in WTE combustion described on page 1-21 (second full paragraph) are unclear. Is plant based carbon (other than PLA and paperboard) included in the total carbon content?

  Response: *WTE emissions exclude carbon dioxide emissions from combustion of biomass-derived materials. These emissions are treated as carbon neutral because they return to the atmosphere carbon dioxide that was removed from the atmosphere during the plant's growth cycle.*

- Is space conditioning for retail (page 1-23) significant for water purchased in stores? See, for example, Norris et al (Journal of Industrial Ecology, 6, 59-69, 2003). Appendix H suggests that 40% of electricity use in large grocery stores is due to uses other than refrigeration.

  Response: *Retail store space conditioning was not included in the results for bottled water. A statement has been added to the methodology chapter section "System Components Not Included, Capital Equipment."*

- Although Appendix H describes water chilling and use of ice, it is still not clear why the water chilling leads to much larger energy demand, compared to use of ice.

  Response: *The refrigerator/freezer energy requirements for chilling water and producing ice are based on the energy required to operate the appliance and the percentage of the appliance space per 1000 gallons of water chilled. Ice cubes are modeled as being added as a percentage of the volume of the water in the drinking container, while home refrigeration of water is based on chilling of water in a half-gallon pitcher containing several servings of water. Because a pitcher of water containing several servings occupies more space than the ice added to a single serving, energy required for chilling a serving of water is higher than chilling a serving of water using ice.*

- Why was a distance of 200 miles chosen for the HOD transport distance (page G-3)?

  Response: *This is an estimate which was validated by followup with IBWA.*

- The statement that 99% of GHG emissions are due to carbon dioxide, methane and nitrous oxide seems to ignore the role of refrigerants (page 2-17).

  Response: *The contribution of refrigerant emissions to the total GWP for bottled water systems is negligible in comparison to the contribution of carbon dioxide, methane, and nitrous oxide emissions.*

- The description of uncertainties in life cycle impact assessments of certain metals (page 3-4) could be equally well applied to many impact categories. The authors should make clear that these issues are not just restricted to metals.

Response: *It is true that uncertainty is an issue for many impact categories; however, ecotoxicity of waterborne metal emissions is an issue that has been the subject of special attention by the LCA community, including convening a special workshop in 2004 and a UNEP/SETAC subgroup to address concerns about waterborne metal ecotoxicity modeling. Concerns about waterborne metal emission ecotoxicity modeling include the need for improved data on speciation (which determines toxicity and bioavailability of the metal emissions), and persistence (taking into account the amount of time that the emissions are bioavailable before they are converted to other species and/or adsorbed to soils, sediments, and suspended matter). Additional description has been added to the report.*

Are the sources of data clearly identified and representative?

Franklin Associates continues to do an outstanding effort to provide data sources and commentary on data quality. When data are given that may not be as representative as wished (such as from confidential discussions when no public data are available), the authors so note. In this report the authors have very clearly identified data sources.

However, two data issues did concern the panel:

- The PLA data from Natureworks comes from a single plant site. The PET data comes from many plants in an industry. It is inappropriate to compare one plant to an industry average without constantly reminding the reader of the difference.

  Response: *NatureWorks is the largest PLA producer and the only company for which PLA production data are available. The report makes mention in numerous places that the PLA results are based on NatureWorks production.*

- The inclusion of wind energy credits is wrong. The use of wind energy is not intrinsic to the manufacture of PLA, but is a business decision by one manufacturer. Any manufacturer could make such promises. Not all PLA producers do. Wind credits should be removed from:

  - All tables, including Tables 2-10, 2-11, 2-12, 2-13, 3.1, 3.2, 3.3, 3.4, 3.5, 3.7, 3.8, 3.9, and 3.10.
  - Figures 2.1, 2.4, 2.6, 2.7, 2.9, 2.10, 3.1, 3.2, 3.4, 3.5, 3.7, 3.10, 3.11, 3.13, 3.14, 3.16, 3.17, 3.19, 3.20, 3.22, 3.23, 3.25, and 3.26.
  - Conclusions other than the reference to PLA6 in Table C-18b.

  Further, the third conclusion on ES-5 needs to omit reference to wind energy credits, since these are a commercial decision. Also, the bullet point on page 2-9 should be omitted.

Response: *After the final draft report had been submitted to the panel for review, we discovered that NatureWorks is no longer purchasing wind credits because of recent process improvements that have significantly reduced their process energy requirements*[42]*. All wind energy references and credits have been removed from the report and appendices. While NatureWorks has published bottom-line energy and greenhouse gas results for PLA from the new (2009) process, published data are not yet available at a level of detail sufficient for LCA modeling by an independent LCA practitioner. A paragraph has been added to the Energy Results section of Chapter 2 and to Appendix C to note that the PLA results do not represent NatureWorks' most recent process developments, due to unavailability of detailed published data needed for LCA modeling.*

- Appendix 1 needs a glossary to define the cases shown in the graphs. The figures and tables and pages need to be renumbered to be consistent with the rest of the report.

  Response: *The modeling parameters scenarios shown in the Appendix 1 graphs are presented in Appendix 1 tables 2-7, 2-8, and 2-9 for bottled water, tap, and HOD, respectively. The results in Appendix 1 are shown for historical context, to illustrate the process of how subscenarios were selected based on runs of an earlier version of the model. Because of subsequent model revisions, the results in the Appendix no longer match the results in the full report. Therefore, the reader should avoid comparing results in the Appendix tables with results in the full report.*

Is the report complete, consistent, and transparent?

The report and appendices are generally complete; generally internally consistent; and are transparent. Although the peer reviewers did not replicate all of the calculations, the analysis generally yielded results that seemed reasonable.

- On page 1-22, under "System Components Not Included, Capital Equipment", a sentence should be added that the installation of water distribution piping is not included. For some citizens, piped water is not practical. Piping to individual homes increases the leakage in the piping system, which has been acknowledged for the entire system, not just for the residential users.

  Response: *A statement has been added to this section stating that installation of water distribution piping is not included.*

- Table 3.6 provides information about the consumption of imported (bottled) and local water. For areas with local water supply issues, this may be the most critical data set in the report. The data deserve a set of graphs in Chapter 4. Better still would be the total water consumption, but the panel understands not all of the necessary background information is available. Still, the burden on local water resources can be highlighted from Table 3.6.

42 http://www.natureworksllc.com/news-and-events/press-releases/2009/02-10-09-ingeo-ecoprofile.aspx

Response: *It is potentially misleading to emphasize a reduction in local water use unless it is possible to also quantify the magnitude of corresponding increases in non-local water use for manufacturing the disposable bottles, caps, and packaging.*

- The statement on page C-43 says "Cradle-to-resin energy for PLA as modeled by Franklin (using U.S. corn growing data and the Ecoinvent data set for production of PLA from corn) is approximately 30 million Btu per 1000 lb, compared to 32.4 million Btu per 1000 lb (75.4 MJ/kg) reported for Natureworks PLA production using grid electricity (PLA5)." In Table C-18a the total energy is 18,772+476=19,248 K Btu/K lbs. An error needs correction and all other calculations involving PLA energy need to be checked. Conclusions, such as on page ES-5 need to be confirmed.

  Response: *The discrepancy is due to the energy content of the corn feedstock to PLA production. The 32.4 million Btu total reported by NatureWorks includes the energy content of the corn used as feedstock for PLA. When the corn feedstock energy is added to the process and transportation energy shown in Table C-18a (now Table C-18), the total from the Franklin model corresponds well with NatureWorks' total energy. The comparison including corn feedstock energy was made to check that Franklin's unit process modeling of PLA was producing results similar to NatureWorks' bottom-line cradle-to-resin PLA results. However, Franklin does not include biomass feedstock energy in our energy of material resource accounting, so the PLA results in the report are based on the process and transportation energy shown in Table C-18. A statement has been added to the discussion in Appendix C.*

- Both Tables C-17 (polycarbonate) and Table C-18a (PLA) should list "Water Consumption" and "Not Available". No data do not mean zero use. On page C-105 the statement is made, "Irrigation is used on most corn-growing farms to supplement inadequate rainfall; however, irrigation water use for corn growing is not included in this analysis. This is excluded in order to avoid any potential bias against corn-derived materials, since similar water use data are not available for unit processes leading to the production of other bottled water packaging materials." Data are given for water consumption in the processes for PET, LDPE, and PP. The statement is disingenuous. If no water data are available for PLA, the PLA section on page C-41 should say so. The sentence "This is excluded in order to avoid any potential bias against corn-derived materials, since similar water use data are not available for unit processes leading to the production of other bottled water packaging materials" should be omitted.

  Response: *Figure 10 of a published paper on the LCA of NatureWorks PLA shows cradle-to-resin gross water use of approximately 50 kg of water per kg of PLA, fairly evenly divided between irrigation water and process water.*[43] *Water use data for the*

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[43] Vink et al. "Application of life cycle assessment to NatureWorks™ polylactide (PLA) production." Available at http://www.natureworksllc.com/our-values-and-views/life-cycle-assessment/~/media/Our%20Values%20and%20Views/LifeCycleAssesment/Basic_LCA/NTR_CompleteLCA_1102%20pdf.aspx

subprocesses of corn production (Table C-51) and production of PLA from corn (Table C-18) are not shown in the Appendix tables to protect the confidentiality of the licensed Ecoinvent data set for production of PLA from corn.

The intent of the statement about avoiding potential bias was not to downplay water use in corn growing but rather to address the fact that a complete comparison of cradle-to-material water use cannot be made for PLA and plastic resins because of data gaps for water use in some unit processes. For plastic materials modeled by Franklin for the Plastics Division of the American Chemistry Council, water use data for individual unit processes are shown in the appendix tables where available, but cradle-to-resin water use cannot be modeled because no water use data are available for some upstream processes. There are also water use data gaps in process data sets for production of other materials used for caps, packaging materials, and reusable drinking containers. The bias statement has been removed as suggested.

- The text on A-11 notes carbon dioxide is present in extracted natural gas. Yet Table A-2 has no listing for CO_2. The fate of the extracted carbon dioxide should be noted as reinjected or released.

  Response: *Detailed information on carbon dioxide emissions from natural gas processing are not readily available. The U.S. EPA document AP-42,* ***Compilation of Air Pollutant Emission Factors****, used as a primary source of emissions data for U.S. LCI process modeling, does not report any CO_2 emissions from natural gas processing.*[44] *The report* ***Natural Gas Processing: The Crucial Link Between Natural Gas Production and Its Transportation to Market*** *states that for natural gas processing facilities that produce large quantities of carbon dioxide, the carbon dioxide is "used primarily for re-injection in support of tertiary enhanced oil recovery efforts in the local production area. The smaller, uneconomic, amounts of carbon dioxide that are normally removed during the natural gas processing and treatment in the United States are vented to the atmosphere."* [45] *A description of sulfur and carbon dioxide removal during natural gas processing found at* *http://www.naturalgas.org/naturalgas/processing_ng.asp* *focuses on sulfur removal by the amine process and does not describe carbon dioxide removal except to note "Although most sour gas sweetening involves the amine absorption process, it is also possible to use solid desiccants like iron sponges to remove the sulfide and carbon dioxide."*

  An estimate of carbon dioxide emissions from natural gas processing is made here using data in the U.S. EPA ***Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007****,*[46] *and processed natural gas quantities published by the U.S. Department*

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44 http://www.epa.gov/ttnchie1/ap42/ch05/final/c05s03.pdf

45 http://www.eia.doe.gov/pub/oil_gas/natural_gas/feature_articles/2006/ngprocess/ngprocess.pdf

46 http://epa.gov/climatechange/emissions/downloads09/Energy.pdf, Table 3-36 "Non-combustion CO_2 Emissions from Natural Gas Systems"

of Energy[47]. DOE statistics show that 15,663,381 million cu ft of natural gas were processed in 2007, while Table 3-36 of the greenhouse gas inventory shows emissions of 21,189 Gg of non-combustion CO_2 .emissions from natural gas processing in 2007. Converted to the basis used in Appendix Table A-2, this equates to approximately 3 pounds of carbon dioxide emissions per 1000 cubic feet of natural gas processed. This addition is small in comparison to the carbon dioxide equivalents from methane emissions and fuel-related emissions from natural gas production and processing, and would cause about a 2 percent increase in the total CO2 equivalents for production and processing of 1000 cu ft of natural gas. Because natural gas is used as a fuel by all drinking water delivery systems in this analysis, the addition of these emissions would increase the GWP for all systems. However, the effect would be largest on plastic water bottle systems since natural gas is also used as a material feedstock for plastic resins used in the bottles, caps, and film packaging.

- The material flow charts either do or do not show masses. Showing the masses helps transparency. The charts for HDPE (Figure C-1), LDPE (Figure C-3), PP (Figure C-4), PET (C-5), and unbleached paperboard (Figure C-10) would be improved with numerical mass designations on the branches.

  Response: *Numbers have been added to these diagrams.*

Are the conclusions appropriate based on the data and analysis?

The conclusions are generally supported by the data and analysis.

- Franklin has done an impressive job of identifying variables which significantly affect the LCI, and then constructing sensitivity analyses for a range of values for these factors; 48 subscenarios emerged, each with a different point value result. Chapter 4 condenses these 48 results into easy to read bar charts, and draws conclusions on the overlap of bands created by these point values. However, somewhere in all the data generated the concept of variability in the 48 point estimates appears to have been overlooked. For example, Franklin studies normally assume a 10% variation in energy estimates. Therefore, energy conclusions shouldn't be drawn on bands created strictly by the point estimates, but rather on these regions expanded to minus 10% of the lowest point value and plus 10% of the highest point value.

Response: *The suggested adjustment has been made to the LCI results figures in Chapter 4.*

Franklin has been a leader in considering when the difference of two numbers represents likely statistical significance. A statement such as "overall differences in energy/greenhouse gas/solid waste of less than X% should not be assumed to be

47 http://tonto.eia.doe.gov/dnav/ng/ng_prod_pp_dcu_nus_a.htm

statistically significant" would be helpful in understanding how to interpret scenario results.

Response: *Guidance on meaningful differences has been added in the introduction to Chapter 4.*

- The authors note there are many scenarios and the relative standings of the three delivery approaches may change with assumptions. The authors also provide the various conventions for partitioning open loop recycling without concluding for or against any of the three presented, as they should.

- The primary study conclusions are three-fold.

➢ First, for systems assumed typically defined, use of tap water and reusable drinking vessels has the least burden, followed by the HOD system and followed by the purchased individual bottle system. ***Comment:*** *It is true that tap water system results are generally lower than HOD and bottled water results except for the "best case" scenarios for HOD and bottled water. However, for overall comparisons of the HOD and bottled water systems, the report notes "When comparing HOD subscenario results and the Oregon bottled water subscenario results, there are many subscenarios where there is overlap between HOD and Oregon bottled water results, even when the best and worst case scenarios are excluded for each system. Therefore, no general statements can be made about which of these systems has lower environmental impacts."*

➢ Second, within the variability of consumer choices and behaviors, the various systems can overlap in most areas of analysis. "Best" and "worst" scenarios for the various systems can overlap.

➢ Third, importing water from distant locations creates more burdens than water sourced in any of the three systems locally.

Adding comments on significance would enhance the report for the user who will make conclusions and decisions.

Response: *See response inserted earlier in this section.*

- On page ES-5 the statement "The energy requirements for PET bottle production per thousand gallons of water delivered are highest for the 8-ounce bottle (scenario 5) because it has the highest ratio of bottle weight to weight of water in the bottle" is not PET specific. A more correct statement would be, "The energy requirements for bottled water delivered in the 8-ounce bottle (scenario 5) is higher than the energy to deliver water in larger bottles because the smaller bottle has a higher ratio of bottle weight to weight of water in the bottle." In fact, neither the 8 oz nor the one liter bottle has been weight optimized. Both are non-standard for water packaging and use carbonated soft drink preforms.

  Response: *The statement has been modified as suggested.*

- On page ES-5 the statement is given "Energy requirements for producing PLA bottles (scenarios 11 through 14 and 25) are somewhat lower than the energy for producing the same size PET bottle, due to lower cradle-to-resin energy requirements for production of PLA compared to PET. In addition, the results for PLA bottles are further reduced when a separate credit is applied for wind energy certificates that are purchased on an ongoing basis by NatureWorks to offset the impacts of electricity used in the production of PLA resin." When wind credits are correctly removed from totals on Table 2.11, there is no justification in claiming lower cradle-to-resin energy requirements for PLA vs. PET, particularly in light of the PLA data set from one plant and the PET numbers from a multi-company industry. The statement should be struck as not substantiated.

  Response: *The bullet point has been removed as suggested.*

- Also on page ES-5 the statement "The choice of recycling methodology also can have a significant effect on the results" refers to LCI allocation conventions, not recycling technology. The sentence should read "The choice of recycling allocation methodology for LCI analysis also can have a significant effect on the results."

  Response: *The statement has been modified as suggested.*

- On ES-5 an additional statement is needed for tap water about the relative difference in washing drinking vessels by hand versus machine.

  Response: *As noted in an earlier response, a paragraph about hand and machine washing of reusable drinking containers has been added to the Scope and Boundaries section.*

- On page ES-6 the statement "Doubling the number of container fills between washings or washing the container every other day instead of daily reduces the washing requirements by half." This statement should also include the warning, "Infrequent washing can lead to accumulation of bacterial contamination".

  Response: *The suggested warning has not been added to the report, to avoid potential misinterpretation by readers who might mistakenly infer that tap water is not as sanitary as bottled water. Since tap water is required to meet stringent standards, bacterial contamination would be due to bacteria from the consumer's mouth contact with the drinking container.*

- On ES-8 the authors have the opportunity to comment on the local potable water usage for single service bottles vs. refilled/washed drinking vessels from the data in Table 3.6. These data point out a key difference in the three systems, a difference that is pertinent and available. A disclaimer can be added about water consumption values are not available for unit processes to make containers.

Response: *It is true that local potable water use for purification and filling of bottled water is lower than local water use for filling and washing of reusable containers; however, while consumption of bottled water avoids the need to use local water for container washing, this may create larger water use burdens elsewhere for production of the bottles and packaging. It is potentially misleading to emphasize a reduction in local water use unless it is possible to also quantify the magnitude of corresponding increases in non-local water use for manufacturing the disposable bottles, caps, and packaging.*

- Page 3-7 includes the statement: "Of the ecotoxicity potential for bottle production, over half is associated with process emissions, primarily waterborne process emissions of metals from crude oil and natural gas extraction. Ecotoxicity results for PLA bottles are lower than for PET bottles, since PLA is not derived from oil and natural gas." This is disingenuous. No farming surface water runoff is included, which will contain phosphates and nitrates (eutrophication contributors) and herbicide/pesticide water contaminants. <u>No data does not mean no emissions</u>. The statement should be modified to reflect the lack of data. The conclusion that plastics derived from oil and natural gas are intrinsically more ecotoxic is unsupported. Tables 3.3 and 3.4 need a footnote that no data on agricultural runoff are included.

  Response: *The section and tables have been modified as suggested.*

<u>Additional Comments</u>

- Under "Systems Studied" on pages ES-2 and 2-2, adding the container sizes studied beside each bottled water material type would help the reader.

  Response: *Sizes have been added as suggested.*

- The intended use statement of the document (page ES-3) is "The primary intended use of the study results is to inform DEQ about the environmental burdens and tradeoffs associated with various options for providing drinking water to consumers". This is good, but incomplete. The various scenarios depend significantly on consumer decisions about purchasing behavior (what percent of a trip's justification was to buy a bottle and container type and size) and cleaning behavior (how often are containers washed and how are they washed). Therefore, the statement should read, "The primary intended use of the study results is to inform DEQ about the environmental burdens and tradeoffs associated with various options for providing drinking water to consumers and behavioral choices of consumers."

  Response: *The statement has been modified as suggested.*

- Approximately 50% of US collected PET is processed in the United States. For Oregon, the export rate may be greater. In any case, the Chinese electrical grid is referenced for the recycled material emissions. No listing is given of the Chinese electrical grid emissions (Page 1-17).

Response: *A description of the Chinese electricity grid mix and the associated CO_2 equivalents per kWh has been added in Appendix J.*

- Franklin Associates has correctly and helpfully included inherent energy (EMR) in Table 2-10.

- Over half of PET water bottle closures are now made of HDPE, not polypropylene. The consequence on final LCI results is expected to be minimal. Also, about half of the PET bottles recycled come with closures on the bottles, and those closures are recycled in open loop recycling. (Page 2-11 refers to not modeling closure recycling.)

  Response: *Based on this comment, some model runs were made to check the effect of these adjustments: a 50:50 mix of HDPE and PP for caps, and a 31% recycling rate for caps (caps recovered with half of the 62% of bottles that are recycled). The effect of modeling a 50:50 mix of HDPE and PP was negligible, and modeling 31% open-loop recycling of caps reduced total energy requirements for the reference PET bottle system by 1% for recycling method 1 and by 2% for recycling methods 2 and 3.*

- The statement on page 3-13, "For the PET bottled water scenarios, the majority of ODP is associated with secondary packaging: process emissions of HCFC-22 associated with production of LDPE film case wrap…" needs explanation. Since it has such a major impact, the report needs to explain why HCFC-22 is part of the LDPE film production. Air is chilled for bubble production. Old chillers might have used HCFC-22 in the past, but it is being phased out next year. Further, if the HCFC-22 statement about LDPE is legitimate, it should also apply to LDPE film used for PLA bottles and for glass bottles.

  Response: *The HCFC-22 emissions are not from the film manufacturing process but from production of LDPE resin, as reported by producers providing process data for the ACC plastic resin database. The same LDPE data set was used for film packaging for the PLA and glass bottled water systems.*

- The Figures in Chapter 4 would be improved if the values for the reference cases were noted.

  Response: *For each drinking water system, the reference case is not intended to be used as an "average" benchmark but rather is used as a reference set of parameters that are varied to construct different subscenarios. Therefore, the results value for the reference scenario is not marked in the figures.*

- Whether the SO_2 emissions listed for diesel fuel in Table A-19 are current needs to be confirmed.

Response: *The diesel fuel combustion emissions, as well as combustion emissions for other types of fuels, were updated for this project with data from GREET 1.8b.*

- Drying is necessary for hygroscopic plastic resins (PET, PC, PLA, copolyester). Drying should be included for Tables D-1, D-2, D-4a, and D-4b, and so stated in the text.

  Response: *The data sets for plastic resin molding (drawn from past Franklin studies and published data) did not clearly identify whether or not the energy requirements included resin drying. Therefore, it is possible that the energy requirements for items made from the resins listed above may be understated. Electricity requirements for drying virgin bottle-grade PET were estimated based on resin throughput, drying times, and kWh requirements from a dryer manufacturer's equipment specifications for medium dryers and large dryers with temperature controlled hoppers.*[48] *The estimated resin drying energy requirements would increase the total life cycle energy requirements for subscenario 1 (an average weight 16.9 ounce virgin PET bottle at 62 percent recycling) by less than 2 percent.*

- The conversion electricity for polypropylene on Table D-3 seems high, particularly compared to other high-temperature melting plastics which must be dried (PET and PC). The Boustead plastics conversion values often include extraneous categories.

  Response: *The Boustead data for injection molding are similar to injection molding data collected by Franklin.*

- The aluminum fabrication energy to extrude and spin form an aluminum bottle needs to be confirmed. The value in Table D-6 appears about half of what is expected.

  Response: *Process data on spin forming were not identified, so the fabrication process energy was modeled based on aluminum casting energy from a 1999 energy and environmental profile of metal casting processes conducted for the Department of Energy by Energetics. Although the data used may understate aluminum bottle fabrication energy, reusable container manufacturing impacts are low when allocated over the estimated number of lifetime uses.*

- Table H-1 lists KWH per square foot to refrigerate in a retail store. Somewhere the value for gallons of water per square foot is needed for transparency.

  Response: *A typical diameter for an individual 16.9 ounce bottle of water is 2 to 2.5 inches. For a rectangular array of 2-inch bottles, 36 bottles (containing 4.6 gallons)*

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48 http://www.conairnet.com/product/documents/Drying%20spec%20sheets/W%20Models%20150%20to%20400.pdf, http://www.conairnet.com/product/documents/Drying%20spec%20sheets/W%20Models%20600%20to%205000.pdf http://www.conairnet.com/product/documents/Drying%20spec%20sheets/Hopper%20Temperature%20Controller.pdf

would fit in a square foot of refrigerated shelf space. Although energy requirements for store refrigeration are shown in the appendices, it should be noted that none of the bottled water subscenarios modeled in the LCA include refrigerated chilling in retail stores. The only bottled water chilling subscenarios modeled were for chilling in a home refrigerator (subscenarios 21 and 24).

- A value is missing on Table J-5 for single unit truck, curbside, ton-miles.

  Response: *Gallons of diesel fuel for the two collection methods are calculated differently. Fuel use for curbside collection is calculated based on the packer truck density of the collected material, the volume of the truck, the distance traveled, and the fuel consumption per mile traveled. Gallons for transport of material collected via deposit drop-offs are calculated based on ton-miles traveled by a truck filled with deposit containers. A footnote has been added to Table J-5.*

PEER REVIEWER QUALIFICATIONS

Beth H. Quay (Peer Review Chair)

Ms. Quay, formerly Director of Environmental Technical Affairs for The Coca-Cola Company in Atlanta, Georgia is an owner/manager of a family business, Antique & Surplus Auto Parts.

She is also an independent consultant to industry and has chaired five Life Cycle Inventory peer review teams. As chair of peer review teams she reviewed the draft LCI reports and appendices, developed a consensus report for the team, and represented the peer review team on issues raised during the peer review.

Ms. Quay's LCA experience at The Coca-Cola Company included managing and coordinating LCAs of beverage packaging and delivery systems. She participated in the SETAC "Code of Practice" Workshop in Sesimbra, Portugal in 1993, where she chaired the team that developed Chapter 6, "Presentations and Communications." She also served as a member of the U.S. EPA LCA Peer Review Groups on Impact Analysis and Data Quality and participated in the SETAC Workshop, "A Technical Framework for Life Cycle Assessment," in Smuggler's Notch, Vermont in 1990.

Ms. Quay's background at The Coca-Cola Company also included management of environmental issues in company operations worldwide, including evaluation of environmental impacts of proposed packaging designs and development of recycling programs and comprehensive waste management solutions. She represented The Coca-Cola Company at environmental conferences and with industry environmental groups.

Ms. Quay has a Bachelor's Degree in Industrial Engineering (Summa Cum Laude) from Georgia Institute of Technology and has done graduate work in Applied Statistics.

David T. Allen (Peer Review Panel Member)

Dr. David Allen is the Gertz Regents Professor of Chemical Engineering and the Director of the Center for Energy and Environmental Resources at the University of Texas at Austin. His research interests lie in air quality and pollution prevention. He is the author of six books and over 150 papers in these areas. The quality of his research has been recognized by the National Science Foundation (through the Presidential Young Investigator Award), the AT&T Foundation (through an Industrial Ecology Fellowship), the American Institute of Chemical Engineers (through the Cecil Award for contributions to environmental engineering), and the State of Texas (through the Governor's Environmental Excellence Award). Dr. Allen was a lead investigator in one of the largest and most successful air quality studies ever undertaken: the Texas Air Quality Study (www.utexas.edu/research/ceer/texaqs). His current research is focused on using the results from that study to provide a sound scientific basis for air quality management in Texas. In addition, Dr. Allen is actively involved in developing Green Engineering educational materials for the chemical engineering curriculum. His most recent effort is a textbook on design of chemical processes and products, jointly developed with the U.S. EPA.

Dr. Allen has extensive experience in LCA and has served on a number of peer review panels of LCIs. He has taught short courses on LCA for government agencies, private companies and in continuing education programs.

Dr. Allen received his B.S. degree in Chemical Engineering, with distinction, from Cornell University in 1979. His M.S. and Ph.D. degrees in Chemical Engineering were awarded by the California Institute of Technology in 1981 and 1983. He has held visiting faculty appointments at the California Institute of Technology, the University of California, Santa Barbara, and the Department of Energy.

David D. Cornell, P.E. (Peer Review Panel Member)

Mr. Cornell is the principal of the plastics stewardship advisement consultancy DD Cornell Associates LLC. His skill areas include technical assessments, economic modeling, and feasibility studies. Mr. Cornell also serves as Vice President of Recycling for SBA-CCI Inc., a PET resin, packaging, and recycling consultancy, and is the current Technical Director for the Association of Post-Consumer Plastics Recyclers (APR). He is a world renowned expert and speaker on PET stewardship issues and the author of "Recycling Polyesters by Chemical Depolymerization" in Modern Polyesters, as well as the author and section editor for the ACS book, Plastics Recycling: a Pragmatic View.

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Land Quality Division

State of Oregon
Department of Environmental Quality

Life Cycle Assessment of Drinking Water Systems: Bottle Water, Tap Water, and Home/Office Delivery Water

Final Peer-Reviewed Appendix

Prepared for DEQ by
Franklin Associates,
A Division of ERG

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APPENDIX A

ENERGY REQUIREMENTS AND ENVIRONMENTAL EMISSIONS FOR FUEL CONSUMPTION

INTRODUCTION

This appendix provides detailed information about the energy requirements and environmental emissions associated with the production and use of various types of fuels and energy sources. Specifically, this appendix describes production of fuels and generation of electrical power, and is presented in terms of precombustion and combustion components. Precombustion components include the resources consumed, energy used, and environmental emissions that result from mining, refining, and transporting fuels, and includes all steps up to, but not including, their end use, or consumption. The combustion components are the energy and environmental releases from the combustion of fuels used for heat, process energy, and electricity generation. This appendix also develops a standard method for relating electricity consumption to actual fuel usage.

The energy and environmental emissions data shown in this appendix can be used in the evaluation of products or processes using a life cycle approach. For example, if it is known that a particular manufacturing process requires the use of a certain amount of electricity, the data presented in this appendix can be used to allocate the fuel usage and the environmental emissions for generating this amount of electricity. In addition, the data in this appendix can be used to calculate the fuel usage and environmental emissions for producing the fuels used to generate this electricity. In this way, the total amount of fuel consumed as well as all of the environmental emissions that result from electricity being used in a particular manufacturing process can be accounted for. Fuel usage by other processes in the manufacture of a product under investigation can be evaluated in a similar manner using the data in this appendix.

While determination of the energy and environmental emissions is logically straightforward, it is complicated by the iterative nature of some of the calculations. For this reason, a roadmap is included for the discussion that follows.

The two main topics in this appendix are a) primary fuel production, and b) primary fuel combustion.

Primary Fuel Production

Primary fuels are the fuels used to produce electricity, generate heat and power, and provide energy for transportation. They include coal, natural gas, residual and distillate fuel oil, and uranium.

The objective is to know both a) the energy (in terms of electricity and primary fuels) required to deliver these fuels to a customer, and b) the environmental emissions resulting from the delivery of these fuels to a customer. (Use of these fuels by a customer is discussed in the section on primary fuel combustion.)

The energy requirements and environmental emissions, starting from the extraction of raw materials from the earth, and ending with the delivery of the processed and refined primary fuels to the customer, are known as **precombustion energy** and **precombustion emissions**. The energy and emissions due to the combustion of these primary fuels by the customer, to produce electricity, to generate heat and power for industrial processes, or to provide energy for transportation are called **combustion energy** and **combustion emissions**.

The energy requirements for the production and processing of primary fuels can be found from industry sources, government surveys, or in the published and unpublished literature. They typically are given in terms of electricity, coal, natural gas, and fuel oil (residual and distillate).

The precombustion energy and environmental emissions can be divided into two sources:

a) the energy and emissions directly related to the extraction and transportation of primary fuels. These are called **direct precombustion energy and emissions**.

b) the energy and emissions more than one step removed from the production of primary fuels. Examples of these include fuels used in the refining of diesel fuel, which is then used in the transportation of coal that is burned by a customer. These fuels, and their associated emissions, are called **indirect precombustion energy and emissions**.

Transportation occurs at several stages along the path to delivering primary fuels for consumption, and must be included in the precombustion components. Coal, for example, is moved from the mine to the utility plant primarily by railroad and barge; oil is transported from the well to the refinery to the customer primarily by pipeline; uranium is transported from the mine to the mill to the enrichment facility to the power plant primarily by truck; and so on.

Data needed are, therefore: a) the fuels used by various modes of transportation (assuming that the modes and distances involved are known), and b) the fuel-related emissions (fuel-related) put out by the transportation steps involved in the stages along the path of delivering primary fuels for consumption.

The fuels used in transportation are included in the **direct precombustion (process) energy** requirements. The fuel-related transportation emissions are included in the **indirect precombustion fuel-related emissions** that are calculated within the LCI model and are not shown separately in this appendix.

The electricity and fuel used to produce the primary fuels require electricity and fuels for their production. Similarly, the fuels used to produce the fuels used to produce the primary fuels also require electricity and fuels for their production. Theoretically, an infinite set of iterations is necessary to account for the electricity and fuels required to deliver the primary fuels for use by a customer.

To account accurately for the fuels used in production and processing of primary fuels, the fuel mix for electricity production in the U.S. must be known, that is, how much coal, natural gas, fuel oil, and uranium are needed to produce one kilowatt-hour of electricity. This is called the composite kilowatt-hour. Knowing the composite kilowatt-hour, the fuels used to generate electricity used in the production of primary fuels can be determined. Then, the total amount of fuels needed to produce the primary fuels can be calculated using input-output techniques, described in more detail later in this appendix.

Emissions to the environment occur whenever fuel is combusted. These **fuel-related precombustion emissions** occur during the production of primary fuels and are determined only after the total fuel requirements for the production of primary fuels have been determined.

Primary Fuel Combustion

The energy and emissions released when fuels are burned are only one part of the energy and emissions associated with the use of a fuel. This part is known as the **combustion components** (i.e., the **combustion energy** and the **combustion emissions**). There are many steps in the production and processing of a fuel before it is usable, and the energy and emissions resulting from these production steps are known as the **precombustion components** (i.e., **precombustion energy** and **precombustion (fuel-related** and **process) emissions)**.

When accounting for the energy and emissions released when fuels are burned, the precombustion components must be added to the combustion components, in order to account for the full environmental burdens associated with the use of the fuels.

Combustion emissions for a given primary fuel will vary according to how it is combusted; for example, coal burned in utility boilers will have a different emissions factor from coal burned in industrial boilers. Major types of combustion sources for the primary fuels, both stationary and mobile, are included in this appendix.

To summarize, the topics included in this appendix are:

- Primary Fuel Production (Precombustion Process Energy Requirements and Precombustion Process Emissions Data)
    - Coal
    - Natural Gas
    - Petroleum Fuels

- Nuclear Fuel
- Energy for Transportation
- Energy Sources for Electricity Generation
    - Calculation of the U.S. Composite Kilowatt-Hour
    - Electricity/Heat Cogeneration
- Precombustion Energy and Emissions for Primary Fuels
- Primary Fuel Combustion
    - Energy Content of Fuels
    - Total Environmental Emissions for Process, Utility, and Transportation Fuels
        - Coal
            - Utility Boilers
            - Industrial Boilers
        - Residual Fuel Oil
            - Utility Boilers
            - Industrial Boilers
        - Distillate Fuel Oil
            - Utility Boilers
            - Industrial Boilers
        - Natural Gas
            - Utility Boilers
            - Industrial Boilers
            - Industrial Equipment
        - Diesel - Industrial Equipment
        - Gasoline - Industrial Equipment
        - Liquefied Petroleum Gases (LPG) - Industrial Equipment
        - Fuel Grade Uranium
        - Wood Wastes
        - Mobile Sources
            - Truck
            - Locomotive
            - Barges
            - Ocean Freighters
            - Cargo Plane

Most of the data included in this appendix were developed by Franklin Associates in 2003 and are based 2000 values. There are exceptions to this time range: Combustion energy values depend on the fuel type and are based on 2005 values (Reference A-116). Crude oil production data are 1997 values, while refinery data are 1995 values. Finally, the profiles of fuels used for electricity production are based on 2004 and 2005 data.

PRIMARY FUEL PRODUCTION

Precombustion Energy and Process Emissions

The fuel production section of this appendix describes the precombustion process and transportation energy requirements and the precombustion process emissions for the production and processing (extraction, beneficiation, refining, and transportation) of the various primary fuels. These fuels are used to generate electricity, to provide direct process energy, or to provide energy for transportation. These precombustion process energy requirements include the use of electricity and primary fuels to provide heat and/or power for industrial processes.

Precombustion process emissions include all environmental emissions that are released as a direct result of activities associated with producing the primary fuels. The process emissions listed in this fuel production section do not, however, include emissions from the combustion of fuels used to produce process energy. These fuel-related process emissions are calculated within the LCI model and are not shown separately in this appendix. The energy values presented in Tables A-1 through A-5 are the basis for these fuel-related precombustion emissions calculations.

Coal

Coal is used as a fuel for electric power generation and industrial heating and steam generation. Energy is required and environmental consequences are incurred in acquiring coal for fuel. The production and distribution of coal is discussed below. Aspects of coal production and distribution specific to each type coal are noted when necessary.

Anthracite Coal Production

Anthracite is hard and very brittle, dense, shiny black, and homogeneous with no marks or layers (Reference A-1). Unlike the lower rank coals, it has a high percentage of fixed carbon and a low percentage of volatile matter (Reference A-1). All anthracite is mined from coal deposits in the eastern United States. The leading coal deposits in the eastern United States are in the Appalachian Region, an area encompassing more than 72,000 square miles and parts of nine states (Reference A-16). The region contains the nation's principal deposits of anthracite (in northeastern Pennsylvania) as well as large deposits of bituminous coal (Reference A-16). A small region of anthracite is present in Arkansas (Reference A-16).

Coal may be obtained by surface mining of outcrops and seams near the earth's surface or by underground mining of deeper deposits. In surface mining, also called strip mining, the overburden (soil and rock covering the ore) is removed from shallow seams, the deposit is broken up, and the coal is loaded for transport. The overburden is generally returned to the mine (eventually) and is not considered as a solid waste in this appendix. Underground mining is done primarily by one of two methods—room-and-pillar mining or longwall mining. Underground mining is a complex undertaking, and is much more labor and energy intensive than surface mining.

After coal is mined, it goes through various preparation processes before it is used as fuel. These processes vary depending on the quality of the coal and the use for which it is intended. Coal preparation usually involves some type of size reduction, such as crushing and screening, and the removal of extraneous material introduced during mining. In addition, coal is often cleaned to upgrade the quality and heating value of the coal by removing or reducing the sulfur, clay, rock, and other ash-producing materials (Reference A-2).

Surface mining is used to extract 95 percent of the U.S. supply anthracite coal, while underground mining extracts 5 percent (Reference A-13). Approximately 64 percent of anthracite coal is cleaned (References A-9 and A-10). Small amounts of solid waste are produced from underground mining, while the remainder of solid waste comes from cleaning.

The coal industry depends heavily on the transportation network for delivering coal to domestic customers. The flow of coal is carried by railroads, barges, ships, trucks, conveyors, and a slurry pipeline. Coal deliveries are usually handled by a combination of transportation modes before finally reaching the consumer (Reference A-1).

The primary air emissions from coal mining are particulates and methane. Particulate emissions arise from coal dust and other debris from stock piles, loaded railroad cars, crushers, conveyors, and other coal processing equipment (References A-4, A-6, and A-7). Methane is released from coal mining operations and continues to be released by coal while it is transported and cleaned (Reference A-8). Factors that influence the extent of particulate and methane emissions include the mining method (surface or underground), the size and location of the mine, and the type of coal.

Table A-1a

DATA FOR MINING AND PROCESSING 1,000 POUNDS OF ANTHRACITE COAL

Energy Usage		
Process Energy		
Electricity	9.61	kwh
Natural Gas	3.72	cubic feet
Residual Oil	0.16	gal
Distillate Oil	0.44	gal
Gasoline	0.032	gal
Anthracite Coal	0.38	lb
Transportation Energy		
Combination Truck	80.4	ton-miles
Diesel	0.84	gal
Process Atmospheric Emissions		
Particulates (unspecified)	2.10	lb
VOC	0.032	lb
Methane	1.59	lb
Process Waterborne Emissions		
Suspended Solids	0.26	lb
Manganese	0.015	lb
Iron	0.022	lb
Process Solid Wastes	271	lbs

References: A-3, A-5, A-11 through A-20, A-105 through A-109.

Source: Franklin Associates, A Division of ERG

Bituminous Coal Production

Bituminous coal is the most abundant rank of coal; it is soft and contains high levels of volatile compounds. Subbituminous coal is softer than bituminous coal. Bituminous and subbituminous are the main types of coal used for electric power generation in the U.S. These types of coal come from 21 states across the U.S. The three top producing states are Wyoming, West Virginia, and Kentucky. Since the properties and uses of subbituminous coal are similar to those for bituminous coal, this appendix aggregates bituminous and subbituminous coals into one category.

Surface mining is used to extract 58 percent of the U.S. supply of bituminous and subbituminous coal, while underground mining extracts 42 percent (Reference A-13). Approximately 58 percent of coal is cleaned (References A-9 and A-10). Small amounts of solid waste are produced from underground mining, while the remainder of solid waste comes from cleaning. New Source Performance Standards (Reference A-11) are used to estimate the water emissions from mining and cleaning bituminous/subbituminous coal. The lower standards for suspended solids recently set for the western (low precipitation) states were also taken into account.

Coal can be obtained by surface mining of outcrops and seams that are near the earth's surface or by underground mining of deeper deposits. In surface mining, also called strip mining, the overburden (soil and rock covering the ore) is removed from shallow seams, the deposit is broken up, and the coal is loaded for transport. The overburden is usually returned to the mine and is thus not considered a solid waste in this appendix. Underground mining is done primarily by one of two methods—room-and-pillar mining or longwall mining. Underground mining is a complex undertaking, and is much more labor and energy intensive than surface mining.

After coal is mined, it goes through various preparation processes before it is used as fuel. These processes vary depending on the quality of the coal and the use for which it is intended. Coal preparation usually involves some type of size reduction, such as crushing and screening, and the removal of extraneous material introduced during mining. In addition, coal is often cleaned to upgrade the quality and heating value of the coal by removing or reducing the sulfur, clay, rock, and other ash-producing materials (Reference A-2).

The coal industry depends heavily on the transportation network for delivering coal to domestic customers. The flow of coal is carried by railroads, barges, ships, trucks, conveyors, and a slurry pipeline. Coal deliveries are usually handled by a combination of transportation modes before finally reaching the consumer (Reference A-1).

The primary air emissions from coal mining are particulates and methane. Particulate emissions arise from coal dust and other debris from stock piles, loaded railroad cars, crushers, conveyors, and other coal processing equipment (References A-4, A-6, and A-7). Methane is released from coal mining operations and continues to be released by coal while it is transported and cleaned (Reference A-8). Factors that influence the extent of particulate and methane emissions include the mining method (surface or underground), the size and location of the mine, and the type of coal.

Table A-1b

DATA FOR MINING AND PROCESSING 1,000 POUNDS OF BITUMINOUS AND SUBBITUMINOUS COAL

Energy Usage		
Process Energy		
Electricity	17.6	kwh
Natural Gas	2.59	cubic feet
Residual Oil	0.10	gal
Distillate Oil	1.05	gal
Gasoline	0.10	gal
Bituminous Coal	0.43	lb
Transportation Energy		
Combination Truck	2.14	ton-miles
Diesel	0.022	gal
Rail	324	ton-miles
Diesel	0.80	gal
Barge	39.3	ton-miles
Diesel	0.031	gal
Residual Oil	0.10	gal
Pipeline-coal slurry	1.56	ton-miles
Electricity	0.37	kwh
Process Atmospheric Emissions		
Particulates (unspecified)	1.63	lb
VOC	0.026	lb
Methane	3.99	lb
Process Waterborne Emissions		
Suspended Solids	0.10	lb
Manganese	0.0058	lb
Iron	0.0086	lb
Process Solid Wastes	235	lbs

References: A-3, A-5, A-9 through A-20, A-106, A-107, A-110, and A-111.

Source: Franklin Associates, A Division of ERG

Lignite Coal Production

Lignite coal is comprised of remnants of woody fibers, giving it a brown color and laminar structure. Lignite coal is not hard, but lignite deposits are tough and require heavy force to break up. There are large deposits of lignite in the southern region of the Gulf Coastal Plain that have been used for electricity generation in Texas since the 1970s and in Louisiana since the 1980s (Reference A-16). The most important lignite beds are in a succession of strata known as the Wilcox Group and are generally 3 to 10 feet thick (Reference A-16). The western part of the United States also has lignite deposits. The largest lignite deposit in the U.S. is in the northern Great Plains, underlying parts of North Dakota, South Dakota, and Montana (Reference A-16). Based on data from the 2001 Coal Industry Annual (Reference A-13) 61 percent of lignite coal is mined in Texas, 34 percent is mined in North Dakota, 4 percent is mined in Louisiana, and less than one percent is mined in Montana.

Coal may be obtained by surface mining of outcrops and seams that are near the earth's surface or by underground mining of deeper deposits. In surface mining, also called strip mining, the overburden (soil and rock covering the ore) is removed from shallow seams, the deposit is broken up, and the coal is loaded for transport. The overburden is usually returned to the mine and is thus not considered a solid waste in this appendix. Underground mining is done primarily by one of two methods—room-and-pillar mining or longwall mining. Underground mining is a complex undertaking, and is much more labor and energy intensive than surface mining. Unlike other ranks of coal, which are extracted by both surface and underground mining, all lignite is extracted by surface mining.

After coal is mined, it goes through various preparation processes before it is used as fuel. These processes vary depending on the quality of the coal and the use for which it is intended. Coal preparation usually involves some type of size reduction, such as crushing and screening, and the removal of extraneous material introduced during mining. In addition, coal is often cleaned to upgrade the quality and heating value of the coal by removing or reducing the sulfur, clay, rock, and other ash-producing materials (Reference A-2). Due to the relatively low value of lignite coal, mining companies do not clean it, but merely crush and screen it before being sent to a power plant (References A-13, A-21, A-22, and A-23).

The coal industry depends heavily on the transportation network for delivering coal to domestic customers. The flow of coal is carried by railroads, barges, ships, trucks, conveyors, and a slurry pipeline. Coal deliveries are usually handled by a combination of transportation modes before finally reaching the consumer (Reference A-1). The low value of lignite coal, however, does not justify long transportation distances from mine to consumption. Thus, the transportation demands for lignite are less than for other ranks of coal.

The primary air emissions from coal mining are particulates and methane. Particulate emissions arise from coal dust and other debris from stock piles, loaded railroad cars, crushers, conveyors, and other coal processing equipment (References A-4, A-6, and A-7). Methane is released from coal mining operations and continues to be released by coal while it is transported and cleaned (Reference A-8). Factors that influence the extent of particulate and methane emissions include the mining method (surface or underground), the size and location of the mine, and the type of coal.

Table A-1c

DATA FOR MINING AND PROCESSING 1,000 POUNDS OF LIGNITE COAL

Energy Usage		
Process Energy		
Electricity	24.2	kwh
Natural Gas	4.03	cubic feet
Residual Oil	1.79	gal
Distillate Oil	0.17	gal
Gasoline	0.17	gal
Lignite Coal	0.36	lb
Transportation Energy		
Combination Truck	3.42	ton-miles
Diesel	0.036	gal
Rail	0.32	ton-miles
Diesel	7.9E-04	gal
Process Atmospheric Emissions		
Particulates (unspecified)	0.098	lb
Methane	1.13	lb
Process Waterborne Emissions		
Suspended Solids	0.0020	lb
Manganese	1.8E-04	lb
Iron	2.6E-05	lb

References: A-3, A-5, A-10 through A-19, A-21 through A-23, A-106, A-107, A-111 through A-113.

Source: Franklin Associates, A Division of ERG

Natural Gas

Natural gas is a widely used energy resource, since it is a relatively clean and versatile fuel. The major component of natural gas is methane (CH_4). Other components of natural gas include ethane, propane, butane, and heavier hydrocarbons, as well as water vapor, carbon dioxide, nitrogen, and hydrogen sulfides. Table A-2 contains the combined energy requirements and environmental emissions for producing, processing, and transporting natural gas used as a fuel.

Natural Gas Production. Natural gas is extracted from deep underground wells and is usually co-produced with crude oil. Because of its gaseous nature, natural gas flows freely from wells that produce primarily natural gas, but some energy is required to pump natural gas and crude oil mixtures to the surface. All natural gas production in this analysis is based on U.S. production, with an estimated 80 percent of natural gas extracted onshore and 20 percent extracted offshore (Reference A-25).

Atmospheric emissions from natural gas production result primarily from unflared venting. Waterborne wastes result from brines that occur when natural gas is produced in combination with oil. In cases where data represent both crude oil and natural gas extraction, this appendix allocates environmental emissions based on the percent weight of natural gas produced. This appendix also apportions environmental emissions according to the percent share of onshore and offshore extraction.

Energy data for natural gas production were calculated from fuel consumption data for the crude oil and natural gas extraction industry (Reference A-34).

Natural Gas Processing. Once raw natural gas is extracted, it is processed to yield a marketable product. First, the heavier hydrocarbons such as ethane, butane and propane are removed and marketed as liquefied petroleum gas (LPG). Then the water vapor, carbon dioxide, and nitrogen are removed to increase the quality and heating value of the natural gas. If the quantities of removed carbon dioxide are large, they are typically used for reinjection, to support tertiary enhanced recovery of oil, while small uneconomic quantities are usually vented to the atmosphere (Reference A-117). If the natural gas has a high hydrogen sulfide content, it is considered “sour.” Before it is used, hydrogen sulfide is removed by adsorption in an amine solution—a process known as “sweetening.”

Atmospheric emissions result from the flaring of hydrogen sulfide (H2S), the regeneration of glycol solutions, and fugitive emissions of methane. Hydrogen sulfide is a natural component of natural gas and is converted to sulfur dioxide (SO_2) when flared; sulfur dioxide emissions were calculated from EPA emission factors (Reference A-26) and the known hydrogen sulfide content of domestic natural gas (Reference A-27). Glycol solutions are used to dehydrate natural gas, and the regeneration of these solutions result in the release of BTEX (benzene, toluene, ethylbenzene, and xylene) as well as a variety of less toxic organics (Reference A-28). Methane emissions result from fugitive releases as well as venting (Reference A-29). Negligible particulate emissions are produced from natural gas plants, and the relatively low processing temperatures (<1,200 degrees Fahrenheit) prevent the formation of nitrogen oxides (NOx).

Energy data for natural gas processing were calculated from fuel consumption data for the natural gas liquids extraction industry (Reference A-34).

Natural gas is transported primarily by pipeline, but a small percentage is compressed and transported by insulated railcars and tankers (References A-30 and A-33). Transportation data were calculated from the net annual quantities of natural gas imported and exported by each state (Reference A-31).

Table A-2

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 CUBIC FEET OF NATURAL GAS

Energy Usage		
Process Energy		
Electricity	1.28	kwh
Natural Gas	50.3	cubic feet
Residual Oil	0.0048	gallons
Distillate Oil	0.0076	gallons
Gasoline	0.0041	gallons
Transportation Energy		
Natural Gas Pipeline	23.0	ton-miles
Natural Gas	15.9	cu ft
Combination Truck	0.23	ton-miles
Diesel	0.0024	gallons
Rail	0.23	ton-miles
Diesel	5.7E-04	gallons
Process Atmospheric Emissions		
Methane	0.65	lb
Sulfur Dioxide	1.12	lb
VOC	0.035	lb
Benzene	0.0044	lb
Ethylbenzene	5.3E-04	lb
Toluene	0.0068	lb
Xylenes	0.0040	lb
Process Waterborne Emissions		
1-Methylfluorene	2.3E-08	lb
2,4-Dimethylphenol	5.7E-06	lb
2-Methylnapthalene	3.2E-06	lb
2-Hexanone	1.3E-06	lb
4-Methyl-2-Pentanone	8.5E-07	lb
Acetone	2.0E-06	lb
Acid (unspecified)	2.5E-04	lb
Alkylated benzenes	2.0E-06	lb
Alkylated fluorenes	1.2E-07	lb
Alkylated naphthalenes	3.3E-08	lb
Alkylated phenanthrenes	1.4E-08	lb
Aluminum	0.0037	lb
Nitrogen (as ammonia)	0.0030	lb
Arsenic	4.5E-05	lb
Barium	0.058	lb
Benzene	3.4E-04	lb
Benzoic acid	2.1E-04	lb
Beryllium	2.0E-06	lb
BOD	0.035	lb
Boron	6.4E-04	lb
Bromide	0.044	lb
Cadmium	6.5E-06	lb
Calcium	0.65	lb
Chlorides	7.34	lb
Chromium (unspecified)	1.0E-04	lb
Cobalt	4.5E-06	lb
COD	0.058	lb

Table A-2 (Cont'd)

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 CUBIC FEET OF NATURAL GAS

Process Waterborne Emissions	
Copper	2.9E-05 lb
Cresols	1.2E-05 lb
Cyanide	1.5E-08 lb
Cymene	2.0E-08 lb
Dibenzofuran	3.9E-08 lb
Dibenzothiophene	3.1E-08 lb
Ethylbenzene	1.9E-05 lb
Fluorine	7.1E-08 lb
Hardness	2.01 lb
Hexanoic acid	4.3E-05 lb
Hydrocarbons	4.1E-05 lb
Iron	0.012 lb
Lead	6.5E-05 lb
Lithium	0.22 lb
Magnesium	0.13 lb
Manganese	2.1E-04 lb
Mercury	4.0E-08 lb
Methylchloride	8.2E-09 lb
Methyl Ethyl Ketone	1.6E-08 lb
Molybdenum	4.7E-06 lb
Naphthalene	3.7E-06 lb
Nickel	3.6E-05 lb
Oil and grease	0.0039 lb
Organic carbon	0.0010 lb
Pentamethylbenzene	1.5E-08 lb
Phenanthrene	2.6E-08 lb
Phenolic compounds	9.1E-05 lb
Radionuclides (unspecified)	7.6E-12 lb
Selenium	4.5E-07 lb
Silver	4.3E-04 lb
Sodium	2.07 lb
Strontium	0.011 lb
Sulfates	0.015 lb
Sulfur	5.4E-04 lb
Surfactants	2.0E-04 lb
Thallium	4.8E-07 lb
Tin	2.2E-05 lb
Titanium	3.5E-05 lb
Toluene	3.2E-04 lb
Total alkalinity	0.016 lb
Total biphenyls	1.3E-07 lb
Total dibenzothiophenes	4.0E-10 lb
Total dissolved solids	9.05 lb
Total suspended solids	0.13 lb
Vanadium	5.5E-06 lb
Xylene	1.7E-04 lb
Yttrium	1.4E-06 lb
Zinc	1.0E-04 lb
Process Solid Waste	1.23 lb

References: A-24 through A-30, A-32 through A-36.

Source: Franklin Associates, A Division of ERG

Petroleum Fuels

In this study, all gasoline and diesel fuel is modeled as 100% petroleum-derived. However, under legislation signed in 2007, all gasoline sold in Oregon must be blended with 10 percent ethanol after Oregon production of ethanol reaches 40 million gallons per year. All diesel fuel sold in the state must be blended with two percent biodiesel when the production of biodiesel from sources in the Pacific Northwest reaches a level of at least 5 million gallons per year. The biodiesel blending requirement increases to 5 percent when annual production reaches a level of at least 15 million gallons per year. Ethanol and biodiesels are already being blended with gasoline and petroleum-derived diesel in Oregon; however, the volumes used are currently small in comparison to the volumes of petroleum-derived fuels. Therefore, modeling all gasoline and diesel fuel as petroleum-derived is expected to have a negligible effect on the results of this analysis.

Crude Oil Extraction. Oil is produced by drilling into porous rock structures generally located several thousand feet underground. Once an oil deposit is located, numerous holes are drilled and lined with a steel casing. Some oil is brought to the surface by natural pressure in the rock structure, although pumps are usually required to bring oil to the surface. Once oil is on the surface, it is separated from water and stored in tanks before being transported to a refinery. In some cases it is immediately transferred to a pipeline that transports the oil to a larger terminal.

There are two primary sources of waste from crude oil production. The first source is the "oil field brine," or water that is extracted with the oil. The brine goes through a separator at or near the well head in order to remove the oil from the water. These separators are very efficient and leave minimal oil in the water.

According to the American Petroleum Institute, 17.9 billion barrels of brine were produced from crude oil extraction in 1995 (Reference A-37). This equates to a ratio of 5.4 barrels of water per barrel of oil. The majority of this brine (85 percent) is produced by onshore oil production facilities and, since such facilities are prohibited from discharging to surface water (Reference A-38), is injected into wells specifically designed for production-related waters. The remaining 15 percent of brine discharges are from offshore oil production facilities and are assumed to be released to the ocean. Therefore, all waterborne wastes from crude oil production are attributable to the brine released from offshore production (Reference A-39). Because crude oil is frequently produced along with natural gas, a portion of the waterborne waste is allocated to natural gas production (Reference A-37).

Evolving technologies are reducing the amount of brine that is extracted during crude oil extraction and minimizing the environmental impact of discharged brine. For example, downhole separation is a technology that separates brine from oil before bringing it to the surface; the brine is injected into subsurface injection zones. The freeze-thaw evaporation (FTE) process is another technology that reduces the discharge of brine by using a freeze crystallization process in the winter and a natural evaporation process in the summer to extract fresh water from brine; the fresh water can be used for horticulture or agricultural applications (Reference A-40).

The second source of waste is gas produced from oil wells. The majority of this gas is recovered for sale, but some is released to the atmosphere. Atmospheric emissions from crude oil production are primarily hydrocarbons. They are attributed to the natural gas produced from combination wells and relate to line or transmission losses and unflared venting. The amount of methane released from crude oil production was calculated from EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks, which has data specific to oil field emissions (Reference A-43).

The requirements for transporting crude oil from the extraction site to the Gulf Coast of the United States (where most petroleum refining in the United States occurs) were calculated from foreign and domestic supply data, port-to-port distance data, and domestic petroleum movement data (References A-41 and A-42). Based on 2001 foreign and domestic supply data, 62 percent of the United States crude oil supply is from foreign sources, 6 percent is from Alaska, and the remaining 32 percent is from the lower 48 states. These percentages were used to apportion transportation requirements among different transportation modes. With the exception of Canada, which transports crude oil to the United States by pipeline, foreign suppliers transport crude oil to the United States by ocean tanker. (In 2001, Saudi Arabia, Mexico, Canada, Venezuela, and Nigeria were the top five foreign suppliers of crude oil to the United States.) The transportation of crude oil from Alaska to the lower 48 states is accomplished by ocean tanker; other domestic transportation of crude oil is accomplished by pipeline and barge.

Table A-3

DATA FOR THE EXTRACTION OF 1,000 POUNDS OF CRUDE OIL

Energy Usage		
Process Energy		
Electricity	17.7	kwh
Natural Gas	525	cubic feet
Residual Oil	0.096	gallons
Distillate Oil	0.15	gallons
Gasoline	0.082	gallons
Transportation Energy		
Petroleum Pipeline	196	ton-miles
Electricity	4.27	kwh
Barge	0.37	ton-miles
Diesel	3.0E-04	gallons
Residual Oil	0.0010	gallons
Ocean Freighter	1,472	ton-miles
Diesel	0.29	gallons
Residual Oil	2.50	gallons
Process Atmospheric Emissions		
Methane	3.53	lb
Process Waterborne Emissions		
1-Methylfluorene	4.0E-07	lb
2,4-Dimethylphenol	1.0E-04	lb
2-Hexanone	2.3E-05	lb
2-Methylnaphthalene	5.6E-05	lb
4-Methyl-2-Pentanone	1.5E-05	lb
Acetone	3.6E-05	lb
Alkylated benzenes	1.7E-04	lb
Alkylated fluorenes	1.0E-05	lb
Alkylated naphthalenes	2.9E-06	lb
Alkylated phenanthrenes	1.2E-06	lb
Aluminum	0.32	lb
Ammonia	0.053	lb
Antimony	2.0E-04	lb
Arsenic	9.8E-04	lb
Barium	4.36	lb
Benzene	0.0060	lb
Benzoic acid	0.0036	lb
Beryllium	5.5E-05	lb
BOD	0.62	lb
Boron	0.011	lb
Bromide	0.76	lb
Cadmium	1.5E-04	lb
Calcium	11.4	lb
Chlorides	128	lb
Chromium (unspecified)	0.0085	lb
Cobalt	7.9E-05	lb
COD	1.02	lb
Copper	0.0010	lb
Cyanide	2.6E-07	lb
Dibenzofuran	6.8E-07	lb
Dibenzothiophene	5.8E-07	lb
Ethylbenzene	3.4E-04	lb
Fluorine	5.0E-06	lb

Table A-3 (Cont'd)

DATA FOR THE EXTRACTION OF
1,000 POUNDS OF CRUDE OIL

Process Waterborne Emissions		
Hardness	35.2	lb
Hexanoic acid	7.5E-04	lb
Iron	0.63	lb
Lead	0.0021	lb
Lead 210	3.7E-13	lb
Lithium	0.0038	lb
Magnesium	2.23	lb
Manganese	0.0036	lb
Mercury	3.5E-06	lb
Methychloride	1.4E-07	lb
Methyl Ethyl Ketone	2.9E-07	lb
Molybdenum	8.2E-05	lb
m-Xylene	1.1E-04	lb
Naphthalene	6.5E-05	lb
n-Decane	1.0E-04	lb
n-Docosane	3.8E-06	lb
n-Dodecane	2.0E-04	lb
n-Eicosane	5.4E-05	lb
n-Hexacosane	2.4E-06	lb
n-Hexadecane	2.1E-04	lb
Nickel	9.8E-04	lb
n-Octadecane	5.3E-05	lb
n-Tetradecane	8.6E-05	lb
o + p-Xylene	7.8E-05	lb
o-Cresol	1.0E-04	lb
Oil and grease	0.072	lb
p-Cresol	1.1E-04	lb
p-Cymene	3.6E-07	lb
Pentamethylbenzene	2.7E-07	lb
Phenanthrene	1.0E-06	lb
Phenol	0.0016	lb
Radium 226	1.3E-10	lb
Selenium	3.9E-05	lb
Silver	0.0075	lb
Sodium	36.2	lb
Strontium	0.19	lb
Sulfates	0.26	lb
Sulfur	0.0094	lb
Surfactants	0.0030	lb
Thallium	4.2E-05	lb
Tin	8.0E-04	lb
Titanium	0.0031	lb
Toluene	0.0056	lb
Total alkalinity	0.28	lb
Total biphenyls	1.1E-05	lb
Total dissolved solids	158	lb
TSS	9.77	lb
Vanadium	9.7E-05	lb
Xylene	0.0028	lb
Yttrium	2.4E-05	lb
Zinc	0.0073	lb
Process Solid Waste	26.1	lb

References: A-24, A-25, A-34 through A-37, A-42, A-43, A-114 through A-117.

Source: Franklin Associates, A Division of ERG

Petroleum Refining. Gasoline and diesel are the primary outputs from refineries; however, other major products include kerosene, aviation fuel, residual oil, lubricating oil, and feedstocks for the petrochemical industry. Data specific to the production of each type of refinery product are not available. Such data would be difficult to characterize because there are many types of conversion processes in oil refineries that are altered depending on market demand, quality of crude input, and other variables. Thus, the following discussion is applicable to all refinery products.

A petroleum refinery processes crude oil into thousands of products using physical and/or chemical processing technology. A petroleum refinery receives crude oil, which is comprised of mixtures of many hydrocarbon compounds and uses distillation processes to separate out pure product streams. Because the crude oil is contaminated (to varying degrees) with compounds of sulfur, nitrogen, oxygen, and metals, cleaning operations are common in all refineries. Also, the natural hydrocarbon components that comprise crude oil are often chemically changed to yield products for which there is higher demand. These processes, such as polymerization, alkylation, reforming, and visbreaking, are used to convert light or heavy crude oil fractions into intermediate weight products, which are more easily handled and used as fuels and/or feedstocks (Reference A-51).

Air pollution is caused by various petroleum refining processes, including vacuum distillation, catalytic cracking, thermal cracking, and sulfur recovery. Fugitive emissions are also significant contributors to air emissions. Fugitive emissions include leaks from valves, seals, flanges, and drains, as well as leaks escaping from storage tanks or during transfer operations. The wastewater treatment plant for a refinery is also a source of fugitive emissions (Reference A-50).

The petroleum refining data represents 1,000 pounds of general refinery product as well as data allocated to specific refinery products. The data are allocated to specific refinery products based on the percent by mass of each product in the refinery output. The mass allocation method assigns energy requirements and environmental emissions equally to all refinery products -- equal masses of different refinery products are assigned equal energy and emissions.

Mass allocation is not the only method that can be used for assigning energy and emissions to refinery products. Heat of combustion and economic value are two additional methods for co-product allocation. Using heat of combustion of refinery products yields allocation factors similar to those derived by mass allocation, demonstrating the correlation between mass and heat of combustion. Economic allocation is complicated because market values fluctuate with supply and demand, and market data are not available for refinery products such as asphalt. This appendix does not apply the heat of combustion or economic allocation methods because they have no apparent advantage over mass allocation.

Table A-4a

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 GALLONS OF RESIDUAL FUEL OIL (excluding crude oil extraction, shown in Table A-3)

Raw Materials		
Crude Oil	8,150	lb
Energy Usage		
Process Energy		
Electricity	512	kwh
Natural Gas	1,402	cu ft
Residual Oil	25.7	gal
LPG	1.09	gal
Transportation Energy		
Combination Truck	108	ton-miles
Diesel	1.13	gal
Rail	68.6	ton-miles
Diesel	0.17	gallons
Barge	581	ton-miles
Diesel	0.46	gal
Residual Oil	1.55	gal
Process Atmospheric Emissions		
Aldehydes	0.33	lb
Ammonia	0.17	lb
Carbon monoxide	105	lb
Carbon tetrachloride	9.2E-08	lb
CFC12	9.1E-07	lb
Hydrocarbons (other than methane)	16.0	lb
Methane	0.56	lb
NOx	2.62	lb
Particulates (unspecified PM)	1.90	lb
SOx (unspecified)	18.5	lb
Trichloroethane	7.7E-07	lb
Process Waterborne Emissions		
BOD5	0.27	lb
COD	1.84	lb
Chromium (hexavalent)	2.9E-04	lb
Chromium (unspecified)	0.0045	lb
Nitrogen (as ammonia)	0.12	lb
Oil and Grease	0.084	lb
Phenolic Compounds	0.0018	lb
Sulfide	0.0015	lb
Total Suspended Solids	0.22	lb
Process Solid Waste	44.2	lb

References: A-36, A-43 through A-49.

Source: Franklin Associates, A Division of ERG

Table A-4b

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 GALLONS OF DISTILLATE FUEL OIL (excluding crude oil extraction, shown in Table A-3)

Raw Materials		
Crude Oil	7,482	lb
Energy Usage		
Process Energy		
Electricity	470	kwh
Natural Gas	1,288	cu ft
Residual Oil	23.6	gal
LPG	1.00	gal
Transportation Energy		
Combination Truck	98.8	ton-miles
Diesel	1.04	gal
Rail	63.0	ton-miles
Diesel	0.16	gallons
Barge	534	ton-miles
Diesel	0.43	gal
Residual Oil	1.42	gal
Petroleum Pipeline	775	ton-miles
Electricity	16.9	kwh
Process Atmospheric Emissions		
Aldehydes	0.30	lb
Ammonia	0.15	lb
Carbon monoxide	96.3	lb
Carbon tetrachloride	8.4E-08	lb
CFC12	8.3E-07	lb
Hydrocarbons (other than methane)	14.7	lb
Methane	0.52	lb
NOx	2.40	lb
Particulates (unspecified PM)	1.74	lb
SOx (unspecified)	17.0	lb
Trichloroethane	7.0E-07	lb
Process Waterborne Emissions		
BOD5	0.25	lb
COD	1.69	lb
Chromium (hexavalent)	2.6E-04	lb
Chromium (unspecified)	0.0041	lb
Nitrogen (as ammonia)	0.11	lb
Oil and Grease	0.077	lb
Phenolic Compounds	0.0016	lb
Sulfide	0.0013	lb
Total Suspended Solids	0.20	lb
Process Solid Waste	40.6	lb

References: A-36, A-43 through A-49.

Source: Franklin Associates, A Division of ERG

Table A-4c

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 GALLONS OF GASOLINE (excluding crude oil extraction, shown in Table A-3)

Raw Materials		
Crude Oil	6,376	lb
Energy Usage		
Process Energy		
Electricity	400	kwh
Natural Gas	1,097	cu ft
Residual Oil	20.1	gal
LPG	0.85	gal
Transportation Energy		
Combination Truck	84.2	ton-miles
Diesel	0.88	gal
Rail	53.7	ton-miles
Diesel	0.13	gallons
Barge	455	ton-miles
Diesel	0.36	gal
Residual Oil	1.21	gal
Petroleum Pipeline	661	ton-miles
Electricity	14.4	kwh
Process Atmospheric Emissions		
Aldehydes	0.26	lb
Ammonia	0.13	lb
Carbon monoxide	82.0	lb
Carbon tetrachloride	7.2E-08	lb
CFC12	7.1E-07	lb
Hydrocarbons (other than methane)	12.5	lb
Methane	0.44	lb
NOx	2.05	lb
Particulates (unspecified PM)	1.49	lb
SOx (unspecified)	14.5	lb
Trichloroethane	6.0E-07	lb
Process Waterborne Emissions		
BOD5	0.21	lb
COD	1.44	lb
Chromium (hexavalent)	2.3E-04	lb
Chromium (unspecified)	0.0035	lb
Nitrogen (as ammonia)	0.095	lb
Oil and Grease	0.066	lb
Phenolic Compounds	0.0014	lb
Sulfide	0.0011	lb
Total Suspended Solids	0.17	lb
Process Solid Waste	34.6	lb

References: A-36, A-43 through A-49.

Source: Franklin Associates, A Division of ERG

Table A-4d

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 GALLONS OF LPG (excluding crude oil extraction, shown in Table A-3)

Raw Materials		
Crude Oil	4,677	lb
Energy Usage		
Process Energy		
Electricity	294	kwh
Natural Gas	805	cu ft
Residual Oil	14.8	gal
LPG	0.62	gal
Transportation Energy		
Combination Truck	61.8	ton-miles
Diesel	0.65	gal
Rail	39.4	ton-miles
Diesel	0.098	gallons
Barge	334	ton-miles
Diesel	0.27	gal
Residual Oil	0.89	gal
Petroleum Pipeline	485	ton-miles
Electricity	10.6	kwh
Process Atmospheric Emissions		
Aldehydes	0.19	lb
Ammonia	0.095	lb
Carbon monoxide	60.2	lb
Carbon tetrachloride	5.3E-08	lb
CFC12	5.2E-07	lb
Hydrocarbons (other than methane)	9.20	lb
Methane	0.32	lb
NOx	1.50	lb
Particulates (unspecified PM)	1.09	lb
SOx (unspecified)	10.6	lb
Trichloroethane	4.4E-07	lb
Process Waterborne Emissions		
BOD5	0.15	lb
COD	1.05	lb
Chromium (hexavalent)	1.7E-04	lb
Chromium (unspecified)	0.0026	lb
Nitrogen (as ammonia)	0.069	lb
Oil and Grease	0.048	lb
Phenolic Compounds	0.0010	lb
Sulfide	8.4E-04	lb
Total Suspended Solids	0.13	lb
Process Solid Waste	25.4	lb

References: A-36, A-43 through A-49.

Source: Franklin Associates, A Division of ERG

Table A-4e

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 GALLONS OF KEROSENE (excluding crude oil extraction, shown in Table A-3)

Raw Materials		
Crude Oil	6,980	lb
Energy Usage		
Process Energy		
Electricity	438	kwh
Natural Gas	1,201	cu ft
Residual Oil	22.0	gal
LPG	0.93	gal
Transportation Energy		
Combination Truck	92.2	ton-miles
Diesel	0.97	gal
Rail	58.8	ton-miles
Diesel	0.15	gallons
Barge	498	ton-miles
Diesel	0.40	gal
Residual Oil	1.32	gal
Petroleum Pipeline	723	ton-miles
Electricity	15.8	kwh
Process Atmospheric Emissions		
Aldehydes	0.28	lb
Ammonia	0.14	lb
Carbon monoxide	89.8	lb
Carbon tetrachloride	7.9E-08	lb
CFC12	7.8E-07	lb
Hydrocarbons (other than methane)	13.7	lb
Methane	0.48	lb
NOx	2.24	lb
Particulates (unspecified PM)	1.63	lb
SOx (unspecified)	15.9	lb
Trichloroethane	6.6E-07	lb
Process Waterborne Emissions		
BOD5	0.23	lb
COD	1.57	lb
Chromium (hexavalent)	2.5E-04	lb
Chromium (unspecified)	0.0038	lb
Nitrogen (as ammonia)	0.10	lb
Oil and Grease	0.072	lb
Phenolic Compounds	0.0015	lb
Sulfide	0.0013	lb
Total Suspended Solids	0.19	lb
Process Solid Waste	37.8	lb

References: A-36, A-43 through A-49.

Source: Franklin Associates, A Division of ERG

Nuclear Fuel

As with other fuels used for the generation of electricity, uranium ore must undergo a series of processing and refining steps before being used in utility plants. These steps include mining, milling, conversion, enrichment, and fuel fabrication. The following sections describe the operations required to process fuel grade uranium for use by the U.S. nuclear power industry.

Mining. Uranium ore can be extracted from the earth by open-pit or underground mining; these methods are referred to as "conventional" mining. Significant amounts of concentrated uranium-containing material can also be produced from solution mining (in-situ leaching), and as a byproduct of phosphate, copper, and beryllium production. Conventional mining ceased in the United States in 1992 when in situ leach (ISL) mining became predominant in Wyoming and Texas (Reference A-60). However, conventional uranium mining is prevalent in Canada, where high-grade uranium deposits can be mined at relatively low costs (Reference A-61).

In 1984, the United States relinquished its role as the principal world producer of uranium to Canada, and Canada has led ever since (Reference A-60). The free trade agreement between the United States and Canada in 1998 has also had an adverse impact on the U.S. uranium industry because U.S. producers cannot compete with Canada's low cost uranium resources (Reference A-60).

Milling. Uranium ore is processed in mills where uranium oxide (U_3O_8, also known as yellowcake) is extracted from the ore by a series of crushing, grinding, and concentration operations. Uranium mills are located near uranium mines due to the large quantities of ore that must be milled to produce concentrated uranium oxide. The most significant waste stream from milling operations is called "tailings." Tailings are liquid sludge from concentration operations. The solids portion of the tailings is separated from the liquid and usually returned to the earth.

Since 1993, all conventional uranium mills in the United States are either inactive, are being decommissioned, or are permanently closed. Only non-conventional uranium plants (in-situ leaching or phosphate byproduct) are currently producing uranium concentrate in the United States.

Conversion. Subsequent to milling, uranium oxide is combined with fluorine gas to form uranium hexafluoride gas (UF_6). In this form, the uranium is ready for enrichment to fuel grade uranium.

Enrichment. Gaseous diffusion and gas centrifuge are the two most common methods used to commercially produce enriched uranium. These enrichment processes increase the fissionable portion of the fuel (U_{235}) from its natural abundance of 0.7 percent to a fuel-grade abundance of approximately 3 percent. Gaseous diffusion is currently used in the United States, while in Europe the gas centrifuge is the prevalent enrichment process. The majority of energy consumption and environmental emissions released in the front-end of the nuclear fuel cycle are due to the enrichment step. (The front-end of the nuclear fuel cycle includes all steps, from mining to fuel fabrication, preceding the consumption of the nuclear fuel.)

In the gaseous diffusion process, gaseous UF_6 is passed through a series of porous membrane filters. In the filtering process, UF_6 molecules containing the U_{235} isotope diffuse through the filters more readily than the molecules containing the larger U_{238} isotope. A typical gaseous diffusion enrichment process requires more than 1,200 stages to produce uranium enriched to 3 percent. Enrichment is necessary for uranium used as fuel in light-water nuclear reactors, because the amount of fissile U_{235} in natural uranium is too low to sustain a nuclear chain reaction.

Fuel Fabrication. Enriched UF_6 is next taken to a fuel fabrication plant, where it is converted to uranium dioxide (UO_2) powder. The powder is compressed into small, cylindrical pellets, which are loaded and sealed into hollow rods made of a zirconium-stainless steel alloy, and then shipped to nuclear power plants. This appendix assumes that the production of the zirconium-stainless steel alloy is insignificant when compared to the uranium fuel itself.

Unlike utilities that require a daily or hourly supply of fuel (such as coal-fired utilities), the fuel for nuclear reactors does not need to be continuously recharged. A fuel load in a nuclear reactor can last up to three years (Reference A-60). This makes the environmental releases and energy requirements of transportation a negligible contributor to the overall environmental profile of the nuclear fuel cycle. It also explains why the sites of uranium mining, milling, conversion, enrichment, and fuel fabrication do not need to be close to the site of consumption.

Table A-5

DATA FOR THE PRODUCTION OF
1,000 POUNDS OF FUEL GRADE URANIUM
(includes mining and milling, conversion,
enrichment, and fuel fabrication)

Energy Usage		
Process Energy		
Electricity	1,851,871	kwh
Bituminous Coal	22,730	pounds
Natural Gas	2,940,070	cu ft
Residual Oil	13.3	gal
Distillate Oil	2,470	gallons
Transportation Energy		
Combination Truck	8,676	ton-miles
Diesel	91.1	gal
Ocean Freighter	24,518	ton-miles
Diesel	4.66	gallons
Residual Oil	41.9	gallons
Process Atmospheric Emissions		
Aldehydes	2.12	lb
Ammonia	167.0	lb
Ammonium chloride	578	lb
Carbon dioxide (fossil)	29,365	lb
Carbon monoxide	466	lb
Fluoride	13.0	lb
Hydrocarbons	3,336	lb
Kerosene	277	lb
NOx	13,780	lb
Organic acids	2.12	lb
Particulates (unspecified)	16,908	lb
Radionuclides	15,477	lb
SOx (unspecified)	17.7	lb
SO2	49,723	lb
Process Waterborne Emissions		
Aluminum	4,541	lb
Ammonium	124	lb
Arsenic	3.77	lb
Cadmium	1.89	lb
Calcium	76.8	lb
Chloride	797	lb
Copper	114.0	lb
Fluoride	2,010	lb
Iron	7,353	lb
Lead	15.90	lb
Manganese	1389	lb
Mercury	0.160	lb
Nitrates	308	lb
Nitrogen (as ammonia)	108	lb
Radionuclides	0.22	ci
Selenium	43.3	lb
Sodium	358	lb
Sulfates	250,520	lb
TSS	7,656	lb
Zinc	193.0	lb
Process Solid Waste	4,884,834	lb

References: A-54 through A-59.

Source: Franklin Associates, A Division of ERG

Energy for Transportation

Transportation, an important step, occurs often in the production of primary fuels. The energy requirements associated with the transportation of products are shown in Table A-6. Transportation modes included are: truck, rail, barge, ocean transport, wide body aircraft, and pipeline. Energy requirements are reported as the quantity of fuel required per 1,000 ton-miles. Statistical data were used for rail, barge, and pipeline transportation energy (References A-88 and A-89).

Table A-6

2000 TRANSPORTATION FUEL REQUIREMENTS

		Fuel Consumed per 1,000 Ton-Miles	Energy Consumed (1) (Btu/ton-mile)
Combination truck (tractor trailer)			
Diesel	gal	10.5	1,682
Gasoline	gal	10.5	1,505
Single unit truck			
Diesel	gal	22.5	3,603
Gasoline	gal	22.5	3,226
Rail			
Diesel	gal	2.5	397
Barge (2)			
Diesel	gal	0.8	128
Residual	gal	2.7	460
Total			588
Ocean freighter (2)			
Diesel	gal	0.2	30
Residual	gal	1.7	296
Total			326
Pipeline - natural gas			
Natural gas	cuft	690	777
Pipeline - petroleum products			
Electricity	kwh	21.8	231
Pipeline - coal slurry			
Electricity	kwh	240	2,548
Air Carrier			
Jet fuel	gal	8.1	1,259

(1) Includes precombustion energy for fuel acquisition.
(2) An average ratio of diesel and residual fuels is used to represent barge and ocean freighter transportation energy.

References: A-88 through A-90, and A-100 through A-104.

Source: Franklin Associates, A Division of ERG

Energy Sources for Electricity Generation

Utility power plants generate electricity from five basic energy sources: coal, fuel oil, natural gas, uranium, and hydropower. A small percentage of electricity is also generated by unconventional sources such as biomass, solar energy, wind energy, and geothermal energy. Wood and wood byproducts are also used to generate electricity, primarily within the forest products industry.

The electricity production and distribution systems in the United States are interlinked and are difficult, if not impossible, to separate from one another. This data module used USEPA's eGRID (Emissions & Generation Resource Integrated Database) to determine the fuel profiles for average US electricity production (Reference A-62). eGRID is a large database that organizes data for electricity generation according to many criteria, including plant-level generation, generator-level generation, state-level generation, NERC region, year, and fuel types. eGRID is a compilation of 24 different data sources from the EPA, Energy Information Administration (EIA), and the Federal Energy Regulatory Commission (FERC). eGRID includes data for individual power plants, generating companies, states, and regions of the electricity grid. Based on the eGRID data, the fuel profile of the 2004 average U.S. electricity grid is shown in Table A-7a.

Since this study includes processes specific to Oregon, the fuel profile of electricity used in Oregon in 2005 is also included in the LCI models. This fuel profile was determined from documentation provided by Oregon DEQ (Reference a-115). The fuel profile for electricity used in Oregon in 2005 is shown in Table A-7b.

Table A-7a

CALCULATION OF ENERGY CONSUMPTION FOR THE GENERATION AND DELIVERY OF ONE COMPOSITE KILOWATT-HOUR, 2004 US AVERAGE

	Total Energy (1)				Quantity of Each Fuel to Generate One KWh		Percent of Composite Kwh (Average US)	Btu of Fuel Consumed per Composite Kwh
Utility Sources								
Bituminous/	Pre-Combustion	530	Btu/lb					
Subbituminous	Combustion	10,655	Btu/lb					
Coal	Total Energy	11,185	Btu/lb		0.97	lb	48.1%	5,221
Lignite Coal	Pre-Combustion	590	Btu/lb					
	Combustion	6,455	Btu/lb					
	Total Energy	7,045	Btu/lb		1.72	lb	3.1%	371
Natural gas	Pre-Combustion	89	Btu/cuft					
	Combustion	1,022	Btu/cuft					
	Total Energy	1,111	Btu/cuft		10.5	cuft	16.5%	1,928
Residual fuel oil	Pre-Combustion	21,900	Btu/gal					
	Combustion	149,700	Btu/gal					
	Total Energy	171,600	Btu/gal		0.070	gal	3.5%	420
Other fossil (2)	Total Energy	10,350	Btu/kwh	(3)	--		1.7%	173.0
Subtotal (fossil fuels)							72.9%	8,113
Uranium	Pre-Combustion	20,400,000	Btu/lb					
	Combustion	985,321,000	Btu/lb					
	Total Energy	1,005,721,000	Btu/lb		6.7E-06	lb	18.6%	1,255
Hydropower	Total energy	3,414	Btu/kwh		--		6.6%	224
Other non-fossil								
Biomass/wood	Total energy	10,350	Btu/kwh	(3)	--		1.2%	129
Geothermal	Total energy	10,350	Btu/kwh	(3)	--		0.3%	35.9
Wind	Total energy	3,414	Btu/kwh		--		0.3%	11.71
Solar	Total energy	3,414	Btu/kwh		--		0.0002%	0.01
TOTAL (U.S. AVERAGE)							**100.0%**	**9,768**
Line loss adjustment: (4)	**Multiply by 1.0991**							**10,736**

(1) From Table A-9.
(2) This is defined by eGRID (Reference A-62) as including tires, chemicals, batteries, hydrogen, sulfur, and waste heat.
(3) 3,414 Btu/kwh divided by 0.33 thermal efficiency
(4) Adjusts energy requirements to account for power losses in transmission lines (i.e., the difference between net electricity generation and sales.) Reference A-62.

Source: Franklin Associates, A Division of ERG

Table A-7b

CALCULATION OF ENERGY CONSUMPTION FOR THE GENERATION AND DELIVERY OF ONE COMPOSITE KILOWATT-HOUR, 2005 OREGON AVERAGE

	Total Energy (1)				Quantity of Each Fuel to Generate One KWh		Percent of Composite Kwh (OR 2005 average) (5)	Btu of Fuel Consumed per Composite Kwh
Utility Sources								
Bituminous/	Pre-Combustion	530	Btu/lb					
Subbituminous	Combustion	10,655	Btu/lb					
Coal	Total Energy	11,185	Btu/lb		0.97	lb	41.0%	4,448
Lignite Coal	Pre-Combustion	590	Btu/lb					
	Combustion	6,455	Btu/lb					
	Total Energy	7,045	Btu/lb		1.72	lb	0%	0
Natural gas	Pre-Combustion	89.0	Btu/cuft					
	Combustion	1,022	Btu/cuft					
	Total Energy	1,111	Btu/cuft		10.5	cuft	10.0%	1,167
Residual fuel oil	Pre-Combustion	21,900	Btu/gal					
	Combustion	149,700	Btu/gal					
	Total Energy	171,600	Btu/gal		0.070	gal	0%	0
Other fossil (2)	Total Energy	10,350	Btu/kwh	(3)	--		0%	0
Subtotal (fossil fuels)							51.0%	5,615
Uranium	Pre-Combustion	20,400,000	Btu/lb					
	Combustion	985,321,000	Btu/lb					
	Total Energy	1,005,721,000	Btu/lb		6.7E-06	lb	3.0%	202
Hydropower	Total energy	3,414	Btu/kwh		--		42.0%	1,434
Other non-fossil								
Biomass/wood	Total energy	10,350	Btu/kwh	(3)	--		3.0%	311
Geothermal	Total energy	10,350	Btu/kwh	(3)	--		0.5%	51.8
Wind	Total energy	3,414	Btu/kwh		--		0.5%	17.1
Solar	Total energy	3,414	Btu/kwh		--		0%	0
TOTAL (OREGON AVERAGE)							**100.0%**	**7,630**
Line loss adjustment: (4)	**Multiply by 1.0991**							**8,386**

(1) From Table A-9.
(2) This is defined by eGRID (Reference A-62) as including tires, chemicals, batteries, hydrogen, sulfur, and waste heat.
(3) 3,414 Btu/kwh divided by 0.33 thermal efficiency
(4) Adjusts energy requirements to account for power losses in transmission lines (i.e., the difference between net electricity generation and sales.) Reference A-62.
(5) Final Report to the Governor: A Framework for Addressing Rapid Climate Change, State of Oregon, January 2008 (Reference A-115)

Source: Franklin Associates, A Division of ERG

Calculation of the U.S. Composite Kilowatt-Hour

A composite kilowatt-hour is defined as a kilowatt-hour of electrical energy produced using the average fuel mix for electricity production for an electricity grid. It is based on the amount of electricity that can be produced from a given quantity of fuel and the percentage of each type of fuel consumed by an electricity grid. The quantities of fuel required to generate one kilowatt-hour are shown in Table A-8. The methods for calculating the amount of electricity that can be produced from each type of fuel in the U.S. electricity grid are discussed below.

The amount of electricity produced per unit of a given fossil fuel (coal, distillate oil, residual oil, and natural gas) can be calculated from the fuel inputs and net electricity production for U.S. utilities (Reference A-63). For example, U.S. utilities produced 1.61 billion megawatt-hours of net electricity from 784 million short tons of bituminous coal in 2000. This translates to 0.97 pounds of bituminous coal per kilowatt-hour of net electricity production. Using the same calculation, the net electricity produced per unit of the other types of fossil fuels were 1.72 pounds per kilowatt-hour for lignite coal, 0.088 gallons per kilowatt-hour for distillate fuel oil, 0.070 gallons per kilowatt-hour for residual fuel oil, and 10.5 cubic feet per kilowatt-hour for natural gas. (Net electricity is the total amount of electricity produced by a utility minus the amount of generated electricity that is consumed by the utility itself.)

For nuclear energy in the U.S., the quantity of uranium fuel (UO_2) consumed per kilowatt-hour of net electricity production was calculated by comparing the quantity of uranium fuel loaded into U.S. nuclear reactors to the kilowatt-hours of electricity produced by U.S. nuclear reactors (References A-92 and A-93). From 1999 through 2001, an annual average of 54.3 million pounds of uranium concentrate (U_3O_8) was used to produce uranium fuel (UO_2) used in U.S. nuclear reactors (Reference A-92). During the same time period, an annual average of 750 billion kilowatt-hours of electricity was generated by U.S. nuclear reactors (Reference A-93). Using a conversion of 10.89 pounds of uranium concentrate per production of one pound of uranium fuel (Reference A-94), 0.0067 pounds of uranium fuel are required for the production of 1,000 kilowatt-hours of electricity. Multiplying this value by the percent of total electricity generated by the nuclear energy results in the quantity of energy contributed by nuclear fuel to the generation of the composite kilowatt-hour.

Efficiency calculations for energy sources other than fossil or nuclear are less meaningful. The quantity of water needed to produce one kilowatt-hour of electricity using hydropower is not an issue in this study. Water for hydropower is a finite, yet renewable, resource. Assigning an efficiency factor to this source of electricity would be an arbitrary procedure. Therefore, the portion of the composite kilowatt-hour from hydropower is determined using the standard conversion of 3,414 Btu per kilowatt-hour and multiplying by the percentage of total electricity generated from hydropower.

Electricity from wind energy and photovoltaic cells (solar energy) falls into the same category as hydroelectric energy. The standard conversion of 3,414 Btu per kilowatt-hour is used to measure energy produced from these sources. Currently, very little electricity is actually being produced using wind energy or photovoltaic cells.

Other non-fossil energy sources, such as geothermal energy, solar energy for steam generation, and biomass energy, currently produce less than one percent of the total electricity generated in the U.S. The contribution from these energy sources is calculated by using the standard conversion factor of 3,414 Btu per kilowatt-hour and assuming an average thermal efficiency of 33 percent for converting the steam produced by these energy sources to electricity. This gives an energy factor of 10,350 Btu per kilowatt-hour of generated electricity. This energy factor is then multiplied by the percentage of total electricity generated from unconventional energy sources.

The composite kilowatt-hour for an electricity grid is calculated from the percent representation of each fuel in the electricity grid and the amount of electricity that can be produced per unit of each type of fuel. For example, to calculate the quantity of natural gas in the U.S. composite kilowatt-hour, the percentage of electricity produced from natural gas in the U.S. (16.5 percent) is multiplied by the amount of natural gas required to produce one kilowatt-hour (10.5 cubic feet), then scaled up by 1.0991 to account for line losses. Thus, the U.S. composite kilowatt-hour includes 1.91 cubic feet of natural gas. This calculation is applied to the remaining fuels and energy sources in order to calculate the total U.S. composite kilowatt-hour.

Table A-8

MIX OF FUEL REQUIRED TO GENERATE ONE KILOWATT-HOUR (1)

		US 2004	**Oregon 2005**
Bituminous/Subbituminus coal	lb	0.51	0.44
Lignite coal	lb	0.058	0
Natural gas	cuft	1.91	1.15
Residual oil	gal	0.0027	0
Other fossil	Btu	190	0
Fuel grade uranium	lb	1.4E-06	2.2E-07
Hydroelectric	Btu	246	1,576
Other non-fossil (2)	Btu	167	379

(1) Calculated from data presented in Table A-7a and A-7b. Includes line loss adjustment.
(2) Other non-fossil includes biomass/wood, geothermal, wind, solar, and other small sources of electricity.

Source: Franklin Associates, A Division of ERG

Electricity/Heat Cogeneration

Cogeneration is the use of steam for generation of both electricity and heat. The most common configuration is to generate high temperature steam in a cogeneration boiler and use that steam to generate electricity. The steam exiting the electricity turbines is then used as a process heat source for other operations. Significant energy savings occur because in a conventional operation, the steam exiting the electricity generation process is condensed, and the heat is dissipated to the environment.

For LCI purposes, the fuel consumed and the emissions generated by the cogeneration boiler need to be allocated to the two energy-consuming processes: electricity generation and subsequent process steam. Because these are both energy-consuming processes, the logical basis for allocation is Btu of energy.

In order to allocate fuel consumption and environmental emissions to both electricity and steam generation, the share of the two forms of energy (electrical and thermal) produced must be correlated to the quantity of fuel consumed by the boiler. Data on the quantity of fuel consumed and the associated environmental emissions from the combustion of the fuel, the amount of electricity generated, and the thermal output of the steam exiting electricity generation must be known in order to allocate fuel consumption and environmental emissions accordingly. These three types of data are discussed below.

1. **Fuels Consumed and Emissions Generated by the Boiler:** The majority of data providers for this study reported natural gas as the fuel used for cogeneration. According to 2003 industry statistics, natural gas accounted for 59 percent of industrial cogeneration, while coal and waste gases accounted for 28 percent and 13 percent, respectively (References A-111 through A-113). For this analysis, the data for the combustion of natural gas in industrial boilers was used to determine the environmental emissions from natural gas combustion in cogeneration boilers. For cases in which coal is used in cogeneration boilers, the data for the combustion of bituminous coal in industrial boilers is recommended. For cases in which waste gas is used in cogeneration boilers, the data for the combustion of LPG (liquefied petroleum gas) in industrial boilers is recommended.

2. **Kilowatt-Hours of Electricity Generated:** In this analysis, the data providers reported the kilowatt-hours of electricity from cogeneration. The Btu of fuel required for this electricity generation was calculated by multiplying the kilowatt-hours of electricity by 6,826 Btu/kWh (which utilizes a thermal to electrical conversion efficiency of 50 percent) (Reference A-110). This Btu value was then divided by the Btu value of fuel consumed in the cogeneration boiler to determine the electricity allocation factor. Note that the kilowatt-hours of electricity generation and consumption of fuel must be on the same production basis, whether a common unit of time or a specified quantity of fuel consumption.

3. **Thermal Output of Steam Exiting Electricity Generation:** In this analysis, the data providers stated the pounds and pressure of steam from cogeneration. The thermal output (in Btu) of this steam was calculated from enthalpy tables (in most cases steam ranged from 1,000 to 1,200 Btu/lb). An efficiency of 80 percent was used for the industrial boiler to calculate the amount of fuel used (Reference A-110). This Btu value was then divided by the Btu value of fuel consumed in the cogeneration boiler to determine the steam allocation factor. Note that the thermal output of steam and consumption of fuel must be on the same production basis, whether a common unit of time or a specified quantity of fuel consumption.

Precombustion Energy and Emissions for Primary Fuels

The energy requirements and environmental emissions, starting from the extraction of raw materials from the earth and ending with the delivery of processed and refined primary fuels to the customer, are referred to here as precombustion energy and precombustion emissions.

Precombustion energy is the sum of all energy inputs into the production of a fuel that is subsequently used as a source of energy. Calculation of precombustion energy requires the tabulation of the fuel requirements for each of the energy sources used in fuel production. Each of these fuel inputs also had energy requirements for production and transportation. This series of inputs creates a complex and technically infinite set of interdependent steps. An input-output model is used to simplify these calculations.

The input-output method used is based on the economic models developed by the economist Wassily Leontief, for which he won the 1973 Nobel Prize in economics.[1] Although Leontief's model tracked dollar flows from one sector of the economy to another, the underlying math also works with the energy content of different fuels, such as coal, natural gas and petroleum products. The purpose of the model is to calculate the total amount of energy required to produce a primary fuel. This includes both the direct energy needed to extract that fuel from the ground, transport, and process it, and all levels of indirect energy (the first level of indirect energy is needed to produce the direct energy, and so on), The energy content of all fuels directly required to produce 1 million Btu of each primary fuel is placed in a matrix. A simplified version of the direct requirements matrix is shown below.

[1] For more information on the underlying mathematics and economic life cycle assessment, see Hendrickson C., L. Lave, and H.S. Matthews, *Environmental Life Cycle Assessment of Goods and Services.* Washington, DC: Resources for the Future. 2006.

Figure A-1. Fuel Input/Output Matrix (partial)

Output Fuels (per MM Btu)

Direct Fuel Requirements (MM Btu)	Electricity	Natural Gas	Residual Oil	Distillate Oil	Diesel	Gasoline	....
Electricity	0	0.0042	0.015	0.016	0.016	0.015	....
Natural Gas	0.54	0.065	0.039	0.039	0.039	0.037	....
Residual Oil	0.094	7.0E-04	0.049	0.049	0.049	0.046	....
Distillate Oil	0	0.0010	0.0012	0.0012	0.0012	0.0011	....
Diesel	0	4.0E-04	0.0039	0.0038	0.0038	0.0036	....
Gasoline	0	5.0E-04	5.6E-04	5.6E-04	5.6E-04	5.3E-04	....
LPG	0	0	7.2E-04	7.1E-04	7.1E-04	6.7E-04	....
Kerosene	0	0	0	0	0	0	....
Anthracite Coal	0	0	0	0	0	0	....
Bituminous	1.65	0	0	0	0	0	....
Lignite	0.093	0	0	0	0	0	....
Uranium	0.42	0	0	0	0	0	....
Precomb Hydro	0.078	0	0	0	0	0	....
Precomb Other + Wood	0.081	0	0	0	0	0	....

From the direct requirements matrix (**A**), a matrix of desired fuel output (**y**), and an identity matrix (**I**), we can find: the desired output itself (**I** × **y**), fuel requirements for the desired output (**A** × **y**), first level indirect fuel requirements (**A** × **A** × **y**), and so on. The total energy requirements for producing a certain amount of fuel can be calculated using the identity:

$$\mathbf{x} = \left(\mathbf{I} + A + A \times A + A \times A \times A + \ldots\right) y = \left(I - A\right)^{-1} y$$

where **x** is the list of total required fuels. Because **x** includes the primary fuels being produced, the precombustion fuels are equal to **x – y**.

Precombustion emissions are the sum of the direct and indirect process emissions from fuel production, and the combustion emissions of all precombustion fuels. Calculation of emissions from precombustion fuels is done by multiplying the matrix from above by a matrix of emissions for each fuel.

Precombustion energy and emissions for primary fuels were calculated using the process and transportation energy requirements already presented in this appendix. The energy data shown in this appendix represent the fuel types and quantities used in the production and delivery of each type of fuel. The emission data shown in this appendix represent the emissions that result from fuel production processes, fuel combustion required for fuel production, and fuel combustion required for transportation.

Precombustion energy requirements for primary fuels were calculated using the process and transportation energy requirements presented in Tables A-1 through A-5, the transportation energy requirements in Table A-6, and the electricity production data presented in Tables A-7, and the energy factors in Table A-9. The results of these calculations are presented in Tables A-10a through A-10c, A-11, A-12a through A-12e, and A-13 for coal, natural gas, petroleum fuels, and nuclear fuels, respectively. The energy requirements shown in Tables A-10 through A-13 include both the process and precombustion energy to produce the fuel.

PRIMARY FUEL COMBUSTION

Energy Content of Fuels

The precombustion, combustion, and total energy associated with the consumption of 1,000 units of the various types of fuels used by mobile and stationary sources are reported in Table A-9. Stationary sources include industrial and utility boilers, and other types of stationary industrial equipment such as compressors and pumps. Mobile sources include various modes of transportation such as truck, rail, barge, and ocean freighter.

Table A-9

ENERGY FACTORS FOR VARIOUS FUELS
2003

		Pre-Combustion Energy (Million Btu)	**Combustion Energy** (Million Btu)	**Total Energy** (Million Btu)
Mobile Sources				
Diesel	1,000 gal	20.1	139	159
Gasoline	1,000 gal	17.1	125	142
Residual fuel oil	1,000 gal	21.9	150	172
Jet fuel (Kerosene)	1,000 gal	18.7	135	154
Industrial Heating				
Anthracite Coal	1,000 lb	0.33	12.4	12.8
Bit/Subbit Coal	1,000 lb	0.53	10.7	11.2
Lignite Coal	1,000 lb	0.59	6.46	7.05
Diesel	1,000 gal	20.1	139	159
Distillate fuel oil	1,000 gal	20.1	139	159
Gasoline	1,000 gal	17.1	125	142
LPG	1,000 gal	12.6	95.5	108
Natural gas	1,000 cuft	0.089	1.03	1.12
Residual fuel oil	1,000 gal	21.9	150	172
Utility Heating				
Anthracite Coal	1,000 lb	0.33	12.4	12.8
Bit/Subbit Coal	1,000 lb	0.53	10.7	11.2
Lignite Coal	1,000 lb	0.59	6.46	7.05
Natural gas	1,000 cuft	0.089	1.02	1.11
Residual fuel oil	1,000 gal	21.9	150	172
Distillate fuel oil	1,000 gal	20.1	139	159
Fuel grade uranium	1,000 lb	20,400	985,320	1,005,720

References: A-81 and A-85.

Source: Franklin Associates, A Division of ERG

Table A-10a

**TOTAL PRECOMBUSTION FUEL USE
FOR THE PRODUCTION OF
1,000 POUNDS OF ANTHRACITE COAL**

Total Precombustion Fuel Use and Process Energy		
Coal - Anthracite	0.38	lb
Coal - Bituminous	5.77	lb
Coal - Lignite	0.54	lb
Natural gas	36.4	cuft
Residual oil	0.26	gal
Distillate oil	1.30	gal
Gasoline	0.034	gal
Liquefied petroleum gas	0.0017	gal
Uranium (nuclear power)	1.6E-05	lb
Hydropower	2,924	Btu
Other renewable energy	1,281	Btu
Wood and wood wastes	1,798	Btu

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, A Division of ERG

Table A-10b

**TOTAL PRECOMBUSTION FUEL USE
FOR THE PRODUCTION OF
1,000 POUNDS OF BITUMINOUS COAL**

Total Precombustion Fuel Use and Process Energy		
Coal - Bituminous	11.6	lb
Coal - Lignite	1.02	lb
Natural gas	58.6	cuft
Residual oil	0.37	gal
Distillate oil	1.95	gal
Gasoline	0.10	gal
Liquefied petroleum gas	0.0026	gal
Uranium (nuclear power)	2.9E-05	lb
Hydropower	5,360	Btu
Other renewable energy	2,348	Btu
Wood and wood wastes	3,296	Btu

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, A Division of ERG

Table A-10c

**TOTAL PRECOMBUSTION FUEL USE
FOR THE PRODUCTION OF
1,000 POUNDS OF LIGNITE COAL**

Total Precombustion Fuel Use and Process Energy		
Coal - Bituminous	14.0	lb
Coal - Lignite	1.66	lb
Natural gas	73.5	cuft
Residual oil	1.98	gal
Distillate oil	0.25	gal
Gasoline	0.17	gal
Liquefied petroleum gas	0.0028	gal
Uranium (nuclear power)	3.8E-05	lb
Hydropower	7,068	Btu
Other renewable energy	3,097	Btu
Wood and wood wastes	4,346	Btu

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, A Division of ERG

Table A-11

**TOTAL PRECOMBUSTION FUEL USE
FOR THE PRODUCTION OF
1,000 CUBIC FEET OF NATURAL GAS**

Total Precombustion Fuel Use and Process Energy		
Coal - Bituminous	0.76	lb
Coal - Lignite	0.070	lb
Natural gas	74.3	cuft
Residual oil	0.010	gal
Distillate oil	0.013	gal
Gasoline	0.0046	gal
Liquefied petroleum gas	3.5E-05	gal
Uranium (nuclear power)	2.1E-06	lb
Hydropower	380	Btu
Other renewable energy	167	Btu
Wood and wood wastes	234	Btu

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, A Division of ERG

Table A-12a

TOTAL PRECOMBUSTION FUEL USE
FOR THE PRODUCTION OF
1,000 GALLONS OF RESIDUAL FUEL OIL

Total Precombustion Fuel Use and Process Energy		
Coal - Bituminous	382	lb
Coal - Lignite	35.5	lb
Natural gas	8,093	cuft
Residual oil	53.5	gal
Distillate oil	6.66	gal
Gasoline	0.80	gal
Liquefied petroleum gas	1.16	gal
Uranium (nuclear power)	0.0011	lb
Hydropower	207,514	Btu
Other renewable energy	90,917	Btu
Wood and wood wastes	127,594	Btu

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, A Division of ERG

Table A-12b

TOTAL PRECOMBUSTION FUEL USE
FOR THE PRODUCTION OF
1,000 GALLONS OF DISTILLATE FUEL OIL

Total Precombustion Fuel Use and Process Energy		
Coal - Bituminous	351	lb
Coal - Lignite	32.6	lb
Natural gas	7,431	cuft
Residual oil	49.2	gal
Distillate oil	6.11	gal
Gasoline	0.73	gal
Liquefied petroleum gas	1.06	gal
Uranium (nuclear power)	0.0010	lb
Hydropower	190,533	Btu
Other renewable energy	83,477	Btu
Wood and wood wastes	117,152	Btu

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, A Division of ERG

Table A-12c

**TOTAL PRECOMBUSTION FUEL USE
FOR THE PRODUCTION OF
1,000 GALLONS OF GASOLINE**

Total Precombustion Fuel Use and Process Energy		
Coal - Bituminous	299	lb
Coal - Lignite	27.8	lb
Natural gas	6,332	cuft
Residual oil	41.9	gal
Distillate oil	5.21	gal
Gasoline	0.63	gal
Liquefied petroleum gas	0.91	gal
Uranium (nuclear power)	8.8E-04	lb
Hydropower	162,363	Btu
Other renewable energy	71,135	Btu
Wood and wood wastes	99,831	Btu

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, A Division of ERG

Table A-12d

**TOTAL PRECOMBUSTION FUEL USE
FOR THE PRODUCTION OF
1,000 GALLONS OF LIQUEFIED PETROLEUM GAS (LPG)**

Total Precombustion Fuel Use and Process Energy		
Coal - Bituminous	219	lb
Coal - Lignite	20.4	lb
Natural gas	4,645	cuft
Residual oil	30.7	gal
Distillate oil	3.82	gal
Gasoline	0.46	gal
Liquefied petroleum gas	0.66	gal
Uranium (nuclear power)	6.5E-04	lb
Hydropower	119,106	Btu
Other renewable energy	52,183	Btu
Wood and wood wastes	73,234	Btu

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, A Division of ERG

Table A-12e

**TOTAL PRECOMBUSTION FUEL USE
FOR THE PRODUCTION OF
1,000 GALLONS OF LIQUEFIED KEROSENE**

Total Precombustion Fuel Use and Process Energy		
Coal - Bituminous	327	lb
Coal - Lignite	30.4	lb
Natural gas	6,932	cuft
Residual oil	45.9	gal
Distillate oil	5.70	gal
Gasoline	0.69	gal
Liquefied petroleum gas	0.99	gal
Uranium (nuclear power)	9.6E-04	lb
Hydropower	177,738	Btu
Other renewable energy	77,871	Btu
Wood and wood wastes	109,285	Btu

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, A Division of ERG

Table A-13

**TOTAL PRECOMBUSTION FUEL USE
FOR THE PRODUCTION OF
1,000 POUNDS OF FUEL-GRADE URANIUM**

Total Precombustion Fuel Use and Process Energy		
Coal - Bituminous	1,027,059	lb
Coal - Lignite	93,320	lb
Natural gas	6,978,489	cuft
Residual oil	5,214	gal
Distillate oil	4,758	gal
Gasoline	163	gal
Liquefied petroleum gas	14.5	gal
Uranium (nuclear power)	2.74	lb
Hydropower	505,588	thousand Btu
Other renewable energy	221,511	thousand Btu
Wood and wood wastes	310,869	thousand Btu

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, A Division of ERG

Combustion Emissions for Process, Utility, and Transportation Fuels

The environmental emissions associated with the combustion of 1,000 units of the various types of fuels by mobile and stationary sources are reported in Tables A-14 through A-24. Mobile sources include various modes of transportation such as truck, rail, barge, etc. Stationary sources include industrial and utility boilers, and other types of stationary industrial equipment such as compressors and pumps. Precombustion emissions for each fuel are calculated within the LCI model using the input-output matrix approach described in the previous section. Since the purpose of these appendices is to document the data used as inputs to the model, the extensive lists of precombustion emissions calculated within the model are not shown in these tables.

Coal

In this section, combustion of different types of coal in utility and industrial boilers are described. There are some differences in combustion emissions for the same types of coal when burned in utility boilers compared to industrial boilers, based on U.S. EPA data sources that report emissions specific to the different types of boilers. Combustion technologies and data sources for each type of coal for each boiler category are described in the following sections.

Utility Boilers.

Anthracite Coal Combustion in Utility Boilers. Anthracite represents a small percentage of utility fuel; bituminous coal is the predominant fuel used in utility boilers (References A-66 and A-70). Anthracite is a high ranking coal with a high heating value and less volatile matter than other coal varieties (Reference A-64). Most anthracite is mined in Pennsylvania, and consumed in Pennsylvania and surrounding states (Reference A-64). Due to its unique composition and limited consumption, the environmental emissions associated with anthracite coal are also unique. The following discussion outlines the calculations and assumptions used for developing an environmental profile for anthracite combustion.

The environmental effects of coal combustion depend on the ash and sulfur content of coal, the type of boiler, and the firing mechanism used. Operational data are not available specifically for boilers that consume anthracite because anthracite is not a primary fuel and is not categorized as a separate group. This appendix assumes a sulfur content of 3 percent and an ash content of 6.5 percent (References A-5 and A-74). Since anthracite is consumed exclusively in Pennsylvania and surrounding states, a boiler profile of Pennsylvania utility boilers was developed in order to estimate the types of boilers used for anthracite combustion (Reference A-70). According to data reported by U.S. utilities (Reference A-70), all utility boilers in Pennsylvania are dry bottom boilers. The majority of these boilers (81.0 percent) use front-firing technologies; tangential-firing (10.2 percent) and opposed-firing (7.7 percent) technologies account for the remainder of anthracite boiler firing technologies (Reference A-75). These above percentages for anthracite composition and boiler properties were used to calculate emissions that are representative of anthracite boilers in U.S. utilities.

Air emissions from utility coal combustion were calculated from EPA sources. EPA's AP-42 database (References A-64 and A-72) includes emission factors for greenhouse gases, particulates, organic compounds, and trace metals. The AP-42 documentation includes emissions that are specific to anthracite coal combustion, but in cases where anthracite data were not available, bituminous coal combustion data were adjusted to represent anthracite combustion. Hazardous air pollutants (HAPs) were estimated from EPA's report to Congress on emissions from utility boilers (Reference A-67).

The emissions of particulates and sulfur oxides depend not only on coal quality and boiler technologies, but also on post-combustion control technologies. Coal-fired power plants commonly employ particulate control devices, which range in efficiency from 80 percent for multiple cyclones to more than 99 percent for electrostatic precipitators and bag filters (Reference A-50). This appendix assumes that an average of 99 percent of the fly ash is collected in particulate control devices. FGD (flue gas desulfurization) controls remove sulfur oxides from post-combustion streams. For utility boilers that burn anthracite coal, the sulfur oxide removal efficiency of FGD controls range from 85 to 99 percent (Reference A-70). However, a majority of anthracite boilers do not employ FGD controls (Reference A-70), and thus the net FGD sulfur oxide removal efficiency for U.S. anthracite utility boilers is approximately 58 percent.

Water emissions represent a small portion of the total environmental emissions from coal-fired utilities (Reference A-67). Water emissions from utility coal combustion were calculated from EPA sources and federal effluent limitations (References A-67 and A-68). Water emissions do not result from the combustion side of coal-fired boilers, but they do result from cooling water and boiler cleaning operations.

Solid waste emissions from coal combustion result from bottom ash, fly ash, boiler slag, and FGD (flue gas desulfurization) wastes. Some solid waste byproducts from utility coal combustion are now being diverted from the landfill by being incorporated in other useful products, such as cement and concrete products, mineral filler in asphalt, grouting, and wall board (Reference A-73). By finding applications for coal combustion byproducts, utilities are reducing their generation of solid waste.

Bituminous Coal Combustion in Utility Boilers. In this appendix, bituminous coal includes the subbituminous coal rank. The composition of bituminous and subbituminous coals are not exactly the same; subbituminous coal has a lower sulfur content and higher moisture content than bituminous coal. However, bituminous and subbituminous coals are used in similar applications, and emission data for their combustion are usually aggregated.

In 2000 over 90 percent of the coal consumed in the U.S. was used by utilities (Reference A-66).The environmental effects of coal combustion depend on the ash and sulfur content of coal, the type of boiler, the firing mechanism used, and the environmental control technologies employed. In 2000 the average sulfur content of coal received by utilities was 1.04 percent by weight, and the average ash content was 8.81

percent by weight (Reference A-66). These averages represent bituminous and subbituminous coal and are weighted according to the 74/26 split between bituminous and subbituminous coal received by utilities in 2000 (Reference A-66). According to data reported by U.S. utilities (Reference A-62), 95 percent of utility boilers fall under one of the following four categories: dry bottom boilers with tangential firing (42 percent), dry bottom boilers with opposed firing (36 percent), dry bottom boilers with front firing (10 percent), and wet bottom boilers with cyclone firing (7 percent). These percentages were used to calculate emissions that are representative of U.S. coal-fired utilities.

Air emissions from utility coal combustion were calculated from EPA sources. EPA’s AP-42 database (Reference A-72) includes emission factors for greenhouse gases, particulates, organic compounds, and trace metals. Greenhouse gas and particulate emissions are also available in EPA’s eGRID database (Reference A-62), which includes reported emissions from U.S. utilities. Hazardous air pollutants (HAPs) were estimated from EPA’s report to Congress on emissions from utility boilers (Reference A-67).

The emissions of particulates and sulfur oxides depend not only on coal quality and boiler technologies, but also on post-combustion control technologies. Coal-fired power plants commonly employ particulate control devices, ranging in efficiency from 80 percent for multiple cyclones to more than 99 percent for electrostatic precipitators and bag filters (Reference A-50). This appendix assumes that an average of 99 percent of the fly ash is collected in particulate control devices. FGD (flue gas desulfurization) controls are used to remove sulfur oxides from post-combustion streams. The average sulfur oxide removal efficiency of existing FGD controls is 85 percent (Reference A-75). The sulfur oxide emissions were reduced to account for the desulfurization units employed by 33 percent of the coal-fired units (Reference A-75).

Water effluents represent a small portion of the total environmental emissions from coal-fired utilities (Reference A-67). Water effluents from utility coal combustion were calculated from EPA sources and federal effluent limitations (References A-67 and A-68). Water effluents do not result from the combustion side of coal-fired boilers, but they do result from cooling water and boiler cleaning operations.

Solid waste emissions from coal combustion result from bottom ash, fly ash, boiler slag, and FGD (flue gas desulfurization) sludge. Some solid waste byproducts from utility coal combustion are diverted from the landfill and incorporated in useful products such as cement and concrete, mineral filler in asphalt, grouting, and wall board (Reference A-73). By finding applications for coal combustion byproducts, utilities are reducing their generation of solid waste.

Lignite Coal Combustion in Utility Boilers. Lignite coal represents a small portion of the total coal consumed by utility boilers. It is not cost-effective to transport lignite, and thus lignite is usually consumed close to the mining site. This restricts most lignite consumption to Texas and North Dakota (Reference A-70).

The environmental effects of coal combustion depend on the ash and sulfur content of coal, the type of boiler, and the firing mechanism used. In 2000 the average sulfur content of lignite coal received by utilities was 0.91 percent by weight, and the average ash content was 14.2 percent by weight (Reference A-69). According to data reported by U.S. utilities (Reference A-70), the majority of utility boilers that consume lignite fall under one of the following five categories: dry bottom boilers with tangential firing (43 percent), dry bottom boilers with concentric firing (22 percent), dry bottom boilers with opposed firing (15 percent), wet bottom boilers with cyclone firing (12 percent), and dry bottom boilers with fluidized bed firing (4 percent). The above percentages for lignite composition and boiler properties were used to calculate emissions that are representative of lignite boilers in U.S. utilities.

Air emissions from utility coal combustion were calculated from EPA sources. EPA's AP-42 database (References A-72 and A-76) includes emission factors for greenhouse gases, particulates, organic compounds, and trace metals. Hazardous air pollutants (HAPs) were estimated from EPA's report to Congress on emissions from utility boilers (Reference A-67).

The emission of particulates and sulfur oxides depend not only on coal quality and boiler technology, but also on post-combustion control technologies. Coal-fired power plants commonly employ particulate control devices, ranging in efficiency from 80 percent for multiple cyclones to more than 99 percent for electrostatic precipitators and bag filters (Reference A-50). This appendix assumes that an average of 99 percent of the fly ash is collected in particulate control devices. FGD (flue gas desulfurization) controls are used to remove sulfur oxides from post-combustion streams. For utility boilers that burn lignite coal, the sulfur oxide removal efficiency of FGD controls ranges from 71 to 99 percent (Reference A-70). However, a majority of lignite utility boilers do not employ FGD controls (Reference A-70), and thus the net FGD sulfur oxide removal efficiency for U.S. lignite utility boilers is approximately 7.8 percent.

Water effluents represent a small portion of the total environmental emissions from coal-fired utilities (Reference A-67). Water effluents from utility coal combustion were calculated from EPA sources and federal effluent limitations (References A-67 and A-68). Water emissions do not result from the combustion side of coal-fired boilers, but they do result from cooling water and boiler cleaning operations.

Solid wastes from coal combustion result from bottom ash, fly ash, boiler slag, and FGD (flue gas desulfurization) sludge. Some solid waste byproducts from utility coal combustion are diverted from the landfill and incorporated in products such as cement and concrete, mineral filler in asphalt, grouting, and wall board (Reference A-73). By finding applications for coal combustion byproducts, utilities are reducing their generation of solid waste.

Combustion emissions for all three types of coal in utility boilers are shown in Table A-14. Precombustion emissions are calculated in the LCI model based on fuel production emissions shown in Tables A-1a through A-5, fuel combustion emissions shown in Tables A-14 through A-24, and precombustion fuel use shown in Tables A-10a through A-10c.

Table A-14

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF COAL IN UTILITY BOILERS (pounds of pollutants per 1,000 pounds of coal)

	Anthracite	Bituminous	Lignite
Atmospheric Emissions			
Particulates (unspecified)	0.026		1.42
Particulates (PM10)		0.094	
Nitrogen Oxides	4.50	6.13	4.43
TNMOC (unspecified)	0.15	0.056	0.029
Sulfur Dioxide	46.5	15.3	6.37
Carbon Monoxide	0.30	0.25	0.13
Fossil CO2	2,840	2,250	1,392
Aldehydes (Formaldehyde)		1.2E-04	1.2E-04
Aldehydes (unspecified)		4.8E-04	4.8E-04
Organics (unspecified)		0.0030	0.0032
Methane	0.020	0.019	0.020
HCl		0.60	0.60
HF		0.075	0.075
Antimony		9.0E-06	9.0E-06
Arsenic	9.5E-05	2.1E-04	2.1E-04
Beryllium	1.6E-04	1.1E-05	1.1E-05
Cadmium	3.6E-05	2.6E-05	2.6E-05
Chromium (VI)		4.0E-05	4.0E-05
Chromium (unspecified)	0.014	1.3E-04	1.3E-04
Cobalt		5.0E-05	5.0E-05
Lead	0.0045	2.1E-04	2.1E-04
Magnesium		0.0055	0.0055
Manganese	0.0018	2.5E-04	2.5E-04
Mercury	6.5E-05	4.2E-05	4.2E-05
Nickel	0.013	1.4E-04	1.4E-04
Selenium	6.5E-04	6.5E-04	6.5E-04
Acrolein		1.5E-04	1.5E-04
Nitrous Oxide	0.018	0.055	0.032
Benzene		6.5E-04	6.5E-04
Perchloroethylene		2.2E-05	2.2E-05
Methylene Chloride		1.5E-04	1.5E-04
Phenols		8.0E-06	8.0E-06
Biphenyl	0.013	8.5E-07	8.5E-07
Acenaphthene		2.6E-07	2.6E-07
Acenaphthylene		1.3E-07	1.3E-07
Anthracene		1.1E-07	1.1E-07
Benzo(a)anthracene		4.0E-08	4.0E-08
Benzo(a)pyrene		1.9E-08	1.9E-08
Benzo(b,j,k)fluroanthene		5.5E-08	5.5E-08
Benzo(g,h,i) perylene		1.4E-08	1.4E-08
Chrysene		5.0E-08	5.0E-08
Fluoranthene		3.6E-07	3.6E-07
Fluorene		4.6E-07	4.6E-07
Indeno(1,2,3-cd)pyrene		3.1E-08	3.1E-08
Naphthalene	0.065	6.5E-06	6.5E-06
Phenanthrene	0.0034	1.4E-06	1.4E-06
Pyrene		1.7E-07	1.7E-07
5-methyl Chrysene		1.1E-08	1.1E-08
Dioxins (unspecified)		3.9E-10	
Furans (unspecified)		2.5E-09	
Radionuclides (unspecified)	3.5E-04	3.5E-04	3.5E-04
Waterborne Emissions			
Suspended Solids	3.3E-04	2.8E-04	1.7E-04
Oil	1.7E-04	1.4E-04	8.7E-05
Solid Waste	38.0	91.7	182

References:

Anthracite: A-5, A-64 through A-72, A-74.
Bituminous: A-16, A-62, A-65 through A-73.
Lignite: A-65, A-67 through A-72, A-74, A-76.

Source: Franklin Associates, A Division of ERG

Industrial Boilers.

Anthracite Coal Combustion in Industrial Boilers. In 2000, 9.4 percent of the coal consumed in the U.S. was used by industry (Reference A-79). Industrial combustion of coal is treated separately from combustion of coal for utility boilers because pollutants are often different. Industries often do not burn coal in boilers as large as or of the same type as the utility boilers. They also do not always burn the same kinds of coal.

Average ash and sulfur content for anthracite coal used by industry was assumed to be the same as for anthracite coal received by utilities. Statistics on coal quality show little difference in the ash and sulfur content between utility and industrial coal (Reference A-84). However, particulate control is generally less efficient for industrial coal boilers, and sulfur oxide controls are rarely employed. According to a representative of the industrial boiler industry, 70 percent of industrial boilers are stoker boilers, 20 percent are FBC (fluidized bed combustion) boilers, and 10 percent are PC (pulverized coal) boilers (Reference A-80). These percentages were used to estimate boiler emissions that are representative of current industry practice.

Air emissions from industrial coal combustion were calculated from EPA sources. The National Air Pollutant Emission Trends database (Reference A-78) includes data for hazardous air pollutants such as carbon monoxide, volatile organic compounds (VOCs), and heavy metal emissions; the AP-42 database (References A-72 and A-64) includes data for greenhouse gases, organic compounds, and trace metals.

Water emissions from industrial coal combustion were calculated from EPA sources and federal effluent limitations (References A-67 and A-68). Water emissions do not result from the combustion side of coal-fired boilers, but they do result from cooling water and boiler cleaning operations. All available data for waterborne emissions were specific to utility boiler emissions, not industrial boiler emissions. Assumptions on the size and applications of industrial boilers were used to adjust utility boiler data so that it was representative of industrial boilers. In particular, since industrial boilers use steam directly for heating industrial processes (Reference A-80 and A-81), it was assumed that there are fewer cooling water requirements for industrial boilers than for utility boilers. Also, since industrial boilers are smaller than utility boilers and require less cleaning (References A-80 and A-81), it was assumed that cleaning wastes are less for industrial boilers than for utility boilers.

Solid waste emissions from coal combustion result from bottom ash, fly ash, boiler slag, and FGD (flue gas desulfurization) wastes. Data for these solid wastes are available for utility boilers, but limited solid waste data are available for industrial boilers. Based on discussions with industry representatives, assumptions were made to adjust utility solid waste data so that they are representative of industrial boilers. In particular, utility boilers are usually equipped with environmental control equipment and thus produce more solid wastes related to the capture of fly ash and FGD. Since few industrial boilers employ environmental control equipment, it was assumed that industrial boilers produce 10 percent of the fly ash and FGD wastes of utility boilers. The reduced solid wastes from industrial boilers, however, translates to higher uncontrolled air emissions.

Bituminous Coal Combustion in Industrial Boilers. In this appendix, bituminous coal includes the subbituminous coal rank. The composition of bituminous and subbituminous coals are not exactly the same; subbituminous coal has a lower sulfur content and higher moisture content than bituminous coal. However, bituminous and subbituminous coals are used in similar applications and available emission data for their combustion are usually aggregated.

In 2000, 9.4 percent of the coal consumed in the U.S. was used by industry (Reference A-79). Industrial combustion of coal is treated separately from combustion of coal for utility boilers because pollutants are often different. Industries often do not burn coal in boilers as large as or of the same type as the utility boilers. They also do not always burn the same kinds of coal. The combustion emissions for industrial boilers are based on AP-42 emission factors for coal combustion in stationary source boilers, while the emissions for utility boilers are based on emissions data reported for coal-fired utilities.

Average ash and sulfur content for bituminous coal used by industry was assumed to be the same as for bituminous coal received by utilities. Statistics on coal quality show little difference in the ash and sulfur content between utility and industrial coal (Reference A-84). However, particulate control is generally less efficient for industrial coal boilers, and sulfur oxide controls are rarely employed. According to a representative of the industrial boiler industry, 70 percent of industrial boilers are stoker boilers, 20 percent are FBC (fluidized bed combustion) boilers, and 10 percent are PC (pulverized coal) boilers (Reference A-80). These percentages were used to estimate boiler emissions that are representative of current industry practice.

Air emissions from industrial coal combustion were calculated from EPA sources. The National Air Pollutant Emission Trends database (Reference A-78) includes data for hazardous air pollutants such as carbon monoxide, volatile organic compounds (VOCs), and heavy metal emissions; the AP-42 database (Reference A-72) includes data for greenhouse gases, organic compounds, and trace metals.

Water emissions from industrial coal combustion were calculated from EPA sources and federal effluent limitations (References A-67 and A-68). Water emissions do not result from the combustion side of coal-fired boilers, but they do result from cooling water and boiler cleaning operations. All available data for waterborne emissions were specific to utility boiler emissions, not industrial boiler emissions. Assumptions on the size and applications of industrial boilers were used to adjust utility boiler data so that it was representative of industrial boilers. In particular, since industrial boilers use steam directly for heating industrial processes (References A-80 and A-81), it was assumed that there are fewer cooling water requirements for industrial boilers than for utility boilers. Also, since industrial boilers are smaller than utility boilers and require less cleaning (References A-80 and A-81), it was assumed that cleaning wastes are less for industrial boilers than for utility boilers.

Solid waste emissions from coal combustion result from bottom ash, fly ash, boiler slag, and FGD (flue gas desulfurization) wastes. Data for these solid wastes are available for utility boilers, but limited solid waste data are available for industrial boilers. Based on discussions with industry representatives, assumptions were made to adjust utility solid waste data so that they are representative of industrial boilers. In particular, utility boilers are usually equipped with environmental control equipment and thus produce more solid wastes related to the capture of fly ash and FGD. Since few industrial boilers employ environmental control equipment, it was assumed that industrial boilers produce 10 percent of the fly ash and FGD wastes of utility boilers. (The reduced solid wastes from industrial boilers, however, translates to higher uncontrolled air emissions.)

Combustion emissions for all three types of coal in industrial boilers are shown in Table A-15. Precombustion emissions are calculated in the LCI model based on fuel production emissions shown in Tables A-1a through A-5, fuel combustion emissions shown in Tables A-14 through A-24, and precombustion fuel use shown in Tables A-10a through A-10c.

Table A-15

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF COAL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 pounds of coal)

	Anthracite	Bituminous	Lignite
Atmospheric Emissions			
Particulates (unspecified)	3.22		8.59
Particulates (PM10)	0.45	2.00	0.37
Nitrogen Oxides	7.12	5.75	5.97
TNMOC (unspecified)	0.068	0.14	0.032
Sulfur Dioxide	45.4	16.6	12.9
Carbon Monoxide	0.68	2.89	0.40
Fossil CO2	2,840	2,634	2,300
Aldehydes (Formaldehyde)	0.0066	0.0034	0.0034
Aldehydes (Acetaldehyde)	3.7E-04	2.9E-04	2.9E-04
Methane	0.020	0.12	0.020
HCl		0.31	0.60
HF	0.50	0.052	0.075
Mercaptan		0.11	
Antimony		9.0E-06	9.0E-06
Arsenic	1.0E-04	1.6E-04	1.6E-04
Beryllium	8.0E-05	7.8E-06	7.8E-06
Cadmium	4.9E-05	4.4E-05	4.4E-05
Chromium (VI)		4.0E-05	4.0E-05
Chromium (unspecified)	0.0070	9.9E-05	9.9E-05
Cobalt		5.0E-05	5.0E-05
Lead	0.0029	0.0018	0.069
Magnesium		0.0055	0.0055
Manganese	9.6E-04	1.8E-04	1.8E-04
Mercury	6.7E-04	6.5E-04	6.5E-04
Nickel	0.0066	1.7E-04	1.7E-04
Selenium	6.5E-04	6.5E-04	6.5E-04
Acetophenone		7.5E-06	7.5E-06
Acrolein	4.4E-06	7.5E-05	7.5E-05
Nitrous Oxide		0.37	
Benzene	0.095	0.048	0.048
Benzyl Chloride		3.5E-04	3.5E-04
Bis(2-ethylhexyl) Phthalate (DEHP)		3.7E-05	3.7E-05
2-Chloroacetophenone		3.5E-06	3.5E-06
Chlorobenzene		1.1E-05	1.1E-05
2,4-Dinitrotoluene		1.4E-07	1.4E-07
Ethyl Chloride		2.1E-05	2.1E-05
Ethylbenzene		4.7E-05	4.7E-05
Ethylene Dibromide		6.0E-07	6.0E-07
Ethylene Dichloride		2.0E-05	2.0E-05
Hexane		3.4E-05	3.4E-05
Isophorone ($C_9H_{14}O$)		2.9E-04	2.9E-04
Methyl Bromide		8.0E-05	8.0E-05
Methyl Chloride		2.7E-04	2.7E-04
Methyl Ethyl Ketone		2.0E-04	2.0E-04
Methyl Hydrazine		8.5E-05	8.5E-05
Methyl Methacrylate		1.0E-05	1.0E-05
Methyl Tert Butyl Ether (MTBE)		1.8E-05	1.8E-05

Table A-15 (cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF COAL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 pounds of coal)

	Anthracite	Bituminous	Lignite
Atmospheric Emissions			
Styrene		1.3E-05	1.3E-05
Toluene		1.2E-04	1.2E-04
Trichloroethane		1.0E-05	1.0E-05
Vinyl Acetate		3.8E-06	3.8E-06
Xylenes		1.9E-05	1.9E-05
Bromoform		2.0E-05	2.0E-05
Chloroform		3.0E-05	3.0E-05
Carbon Disulfide		6.5E-05	6.5E-05
Dimethyl Sulfate		2.4E-05	2.4E-05
Cumene		2.7E-06	2.7E-06
Cyanide		0.0013	0.0013
Perchloroethylene		2.2E-05	2.2E-05
Methylene Chloride		1.5E-04	1.5E-04
Phenols		8.0E-06	8.0E-06
Fluorides		0.022	
Biphenyl	0.013	8.5E-07	8.5E-07
Acenaphthene		2.6E-07	2.6E-07
Acenaphthylene		1.3E-07	1.3E-07
Anthracene		1.1E-07	1.1E-07
Benzo(a)anthracene		4.0E-08	4.0E-08
Benzo(a)pyrene		1.9E-08	1.9E-08
Benzo(b,j,k)fluroanthene		5.5E-08	5.5E-08
Benzo(g,h,i) perylene		1.4E-08	1.4E-08
Chrysene		5.0E-08	5.0E-08
Fluoranthene		3.6E-07	3.6E-07
Fluorene		4.6E-07	4.6E-07
Indeno(1,2,3-cd)pyrene		3.1E-08	3.1E-08
Naphthalene	0.065	6.5E-06	6.5E-06
Phenanthrene	0.0034	1.4E-06	1.4E-06
Pyrene		1.7E-07	1.7E-07
5-methyl Chrysene		1.1E-08	1.1E-08
Dioxins (unspecified)			
Furans (unspecified)			
CFC12			
Radionuclides (unspecified)			
Waterborne Emissions			
Suspended Solids	1.5E-04	1.4E-04	1.1E-04
Oil	7.6E-05	7.0E-05	5.6E-05
Solid Waste	10.6	62.1	61.6

References: .
Anthracite: A-5, A-15, A-64, A-66 through A-68, A-72, A-74, A-77 through A-80, A-82, A-83
Bituminous: A-5, A-15, A-64, A-66 through A-68, A-74, A-77 through A-80, A-82, and A-83.
Lignite: A-5, A-15, A-64, A-66 through A-68, A-74, A-77 through A-80, A-82, A-83, A-112, and A-113.

Source: Franklin Associates, A Division of ERG

Residual Fuel Oil

Utility Boilers. Fuel oils accounted for 2.8 percent of the total megawatt hours produced by electric utilities in 2000 (Reference A-62). Residual fuel oil represents the majority of the fuel oil consumed by electric utilities. The calculations and assumptions used for estimating the environmental emissions from residual fuel oil combustion in utility boilers are discussed below.

Air emissions from residual fuel oil combustion were taken from the GREET model (Reference A-116). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50).

No data are available for waterborne emissions from utility boilers. Waterborne emissions do not result from the combustion-side of utility boilers, but they do result from ancillary processes such as cooling water systems and boiler cleaning operations (Reference A-67). Such emissions were estimated from federal limits on waterborne releases from utility boilers (Reference A-68) and flow rates of water streams from boiler systems (Reference A-67). Waterborne emissions can include low concentrations of metals, resulting from equipment corrosion, and low concentrations of chlorinated compounds, resulting from cleaning chemicals.

Solid waste emissions from fossil fuel combustion result from wastes from environmental controls (particulate and desulfurization controls) and bottom ash. Utilities using oil-fired boilers do not currently employ flue gas desulfurization units (Reference A-69), which eliminates the possibility of solid wastes from desulfurization equipment. To calculate the solid waste resulting from bottom ash, the fly ash emissions (which are assumed to be equivalent to the airborne particulate emissions) were subtracted from the quantity of ash in the incoming fuel. This appendix assumes an ash content 0.16 percent by weight for residual fuel oil (Reference A-67), resulting in an estimated 10.7 pounds of bottom ash per 1,000 gallons of combusted residual fuel oil.

Industrial Boilers. The calculations and assumptions used for estimating the environmental emissions from residual fuel oil combustion in industrial boilers are discussed below.

Air emissions from residual fuel oil combustion were taken from the GREET model (Reference A-116). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (References A-86 and A-50).

No data are available for waterborne emissions from industrial boilers. Waterborne emissions are a negligible part of an industrial facility's total effluent and clean-up system (Reference A-80). Waterborne emissions do not result from the combustion-side of industrial boilers, but they do result from ancillary processes such as cooling water systems and boiler cleaning operations (Reference A-67). Such emissions were estimated from federal limits on waterborne releases (Reference A-68) and flow rates of water streams from boiler systems (Reference A-67). Waterborne emissions can include low concentrations of metals, resulting from equipment corrosion, and low concentrations of chlorinated compounds, resulting from cleaning chemicals.

Solid waste emissions from fossil fuel combustion result from wastes from environmental controls (particulate and desulfurization controls) and bottom ash. Industrial boilers rarely employ flue gas desulfurization units (Reference A-69), which eliminates the possibility of solid wastes from desulfurization equipment. To calculate the solid waste resulting from bottom ash, the fly ash emissions (which are assumed to be equivalent to the airborne particulate emissions) were subtracted from the quantity of ash in the incoming fuel. This appendix assumes an ash content 0.16 percent by weight for residual fuel oil (Reference A-67), resulting in an estimated 10.7 pounds of bottom ash per 1,000 gallons of combusted residual fuel oil.

Combustion emissions for residual oil in utility and industrial boilers are shown in Table A-16. Precombustion emissions are calculated in the LCI model based on fuel production emissions shown in Tables A-1a through A-5, fuel combustion emissions shown in Tables A-14 through A-24, and precombustion fuel use shown in Table A-12a.

Table A-16

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF RESIDUAL FUEL OIL IN BOILERS
(pounds of pollutants per 1,000 gallons of residual oil)

	Utility	Industrial
Atmospheric Emissions		
Particulates (PM10)	6.80	15.5
Particulates (PM2.5)	5.10	10.0
Nitrogen Oxides	30.9	46.4
VOC (unspecified)	0.69	0.28
Sulfur Oxides	68.7	68.7
Carbon Monoxide	4.94	4.94
Fossil CO2	26,292	26,291
Aldehydes (Formaldehyde)	0.033	0.033
Methane	0.28	1.00
HCl	0.70	0.70
Arsenic	0.0013	0.0013
Beryllium	2.8E-05	2.8E-05
Cadmium	4.0E-04	4.0E-04
Chromium (unspecified)	8.5E-04	8.5E-04
Cobalt	0.0060	0.0060
Lead	0.0015	0.0015
Manganese	0.0030	0.0030
Mercury	1.1E-04	1.1E-04
Nickel	0.085	0.085
Selenium	6.8E-04	6.8E-04
Nitrous Oxide	0.11	0.11
Benzene	2.1E-04	2.1E-04
Naphthalene	0.0011	0.0011
Perchloroethylene	8.2E-05	7.0E-05
Methylene Chloride	0.0048	0.0048
Phenols	0.0036	0.0036
Dioxins (unspecified)	1.5E-08	1.5E-08
Radionuclides (unspecified)	1.2E-05	1.0E-05
Waterborne Emissions		
Suspended Solids	0.011	0.011
Oil	0.0054	0.0054
Copper	3.6E-04	3.6E-04
Iron	3.6E-04	3.6E-04
Chlorides (unspecified)	7.2E-05	7.2E-05
Solid Waste	10.7	10.6

References: A-67, A-68, A-70, A-71, A-86, A-88, and A-116.

Source: Franklin Associates, A Division of ERG

Distillate Fuel Oil

Utility Boilers. Distillate fuel oil represents a small percentage of the fuel oil burned by utility boilers. The calculations and assumptions used for estimating the environmental emissions from distillate fuel oil combustion in utility boilers are discussed below.

Air emissions from distillate fuel oil combustion were taken from the GREET model (Reference A-116). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50). No data are available for distillate fuel oil combustion in utility boilers, so distillate fuel oil combustion in industrial boilers was used as a surrogate.

No data are available for waterborne emissions from utility boilers. Waterborne emissions do not result from the combustion-side of utility boilers, but they do result from ancillary processes such as cooling water systems and boiler cleaning operations (Reference A-67). Such emissions were estimated from federal limits on waterborne releases from utility boilers (Reference A-68) and flow rates of water streams from boiler systems (Reference A-67). Waterborne emissions can include low concentrations of metals, resulting from equipment corrosion, and low concentrations of chlorinated compounds, resulting from cleaning chemicals.

Solid waste emissions from fossil fuel combustion result from wastes from environmental controls (particulate and desulfurization controls) and bottom ash. The sulfur content of distillate fuel oil is 0.035 percent by weight (Reference A-85), making desulfurization equipment unnecessary. Distillate fuel oil also has a low ash content (Reference A-67), resulting in negligible quantities of bottom ash as well as eliminating the need for particulate controls. Thus, this appendix assumes that negligible solid wastes result from the combustion of distillate fuel oil in utility boilers.

Industrial Boilers. The calculations and assumptions used for estimating the environmental emissions from distillate fuel oil combustion in industrial boilers are discussed below.

Air emissions from distillate fuel oil combustion were taken from the GREET model (Reference A-116). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50).

No data are available for waterborne emissions from industrial boilers. Waterborne emissions are a negligible part of an industrial facility's total effluent and clean-up system (Reference A-80). Waterborne emissions do not result from the combustion-side of industrial boilers, but they do result from ancillary processes such as cooling water systems and boiler cleaning operations (Reference A-67). Such emissions were estimated from federal limits on waterborne releases (Reference A-68) and flow rates of water streams from boiler systems (Reference A-67). Waterborne emissions can include low concentrations of metals, resulting from equipment corrosion, and low concentrations of chlorinated compounds, resulting from cleaning chemicals.

Solid waste emissions from fossil fuel combustion result from wastes from environmental controls (particulate and desulfurization controls) and bottom ash. The sulfur content of distillate fuel oil is 0.035 percent by weight (Reference A-85), making desulfurization equipment unnecessary. Also, industrial boilers rarely employ desulfurization equipment, regardless of the sulfur content of the fuel. Distillate fuel oil also has a low ash content (Reference A-67), resulting in negligible quantities of bottom ash as well as eliminating the need for particulate controls. Thus, this appendix assumes that negligible solid wastes result from the combustion of distillate fuel oil in utility boilers.

Combustion emissions for distillate oil in utility and industrial boilers are shown in Table A-17. Precombustion emissions are calculated in the LCI model based on fuel production emissions shown in Tables A-1a through A-5, fuel combustion emissions shown in Tables A-14 through A-24, and precombustion fuel use shown in Table A-12b.

Table A-17

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DISTILLATE FUEL OIL IN BOILERS
(pounds of pollutants per 1,000 gallons of distillate oil)

	Utility	Industrial
Atmospheric Emissions		
Particulates (PM10)	13.1	13.1
Particulates (PM2.5)	10.8	10.8
Nitrogen Oxides	23.6	23.6
VOC (unspecified)	0.36	0.36
Sulfur Oxides	2.27	2.27
Carbon Monoxide	4.86	4.86
Fossil CO2	22,116	22,116
Aldehydes (Formaldehyde)	0.033	
Methane	0.051	0.051
HCl	0.70	0.70
Arsenic	0.0013	5.5E-04
Beryllium	2.8E-05	4.2E-04
Cadmium	4.0E-04	4.2E-04
Chromium (unspecified)	8.5E-04	4.2E-04
Cobalt	0.0060	
Copper		8.3E-04
Lead	0.0015	0.0012
Manganese	0.0030	8.3E-04
Mercury	1.1E-04	4.2E-04
Nickel	0.085	4.2E-04
Selenium	6.8E-04	0.0021
Zinc		5.5E-04
Nitrous Oxide	0.11	0.11
Benzene	2.1E-04	
Naphthalene	0.0011	
Perchloroethylene	7.6E-05	7.6E-05
Methylene Chloride	0.0045	0.0045
Phenols	0.0034	0.0034
Dioxins (unspecified)	1.4E-08	1.4E-08
Radionuclides (unspecified)	1.1E-05	1.1E-05
Waterborne Emissions		
Suspended Solids	0.0096	0.0089
Oil	0.0045	0.0045
Copper	3.2E-04	
Iron	3.2E-04	3.0E-04
Chlorides (unspecified)	6.4E-05	5.9E-05

References: A-67, A-68, A-70, A-71, A-86, A-88, and A-116.

Source: Franklin Associates, A Division of ERG

Natural Gas

Utility Boilers. Natural gas represented 15.9 percent of the total megawatt hours produced by U.S. electric utilities in 2000 (Reference A-62). The calculations and assumptions used for estimating the environmental emissions from natural gas combustion in utility boilers are discussed below.

Air emissions from natural gas combustion were taken from the GREET model (Reference A-116). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50). Since natural gas has a low sulfur and ash content, the sulfur dioxide and particulate emissions from natural gas emissions are very low when compared to other fossil fuels. The major pollutants from the burning of natural gas are nitrogen oxides. Nitrogen oxides are usually controlled by adjusting the firing parameters of a boiler.

No data are available for waterborne emissions from utility boilers. Waterborne emissions do not result from the combustion-side of utility boilers, but they do result from ancillary processes such as cooling water systems and boiler cleaning operations (Reference A-67). Since natural gas is a clean burning fuel, this appendix assumes that the cleaning of natural gas boilers is rare and thus produces negligible waterborne emissions (Reference A-95).

Solid waste emissions from fossil fuel combustion result from wastes from environmental controls (particulate and desulfurization controls) and bottom ash. Natural gas is a clean burning fuel with virtually no sulfur or particulate emissions. Thus, desulfurization and particulate controls are not employed for natural gas combustion. Also, due to its low ash content, natural gas combustion produces virtually no bottom ash or other solid wastes (Reference A-67). Thus, this appendix assumes that negligible solid wastes result from the combustion of natural gas in utility boilers.

Industrial Boilers. The calculations and assumptions used for estimating the environmental emissions from natural gas combustion in industrial boilers are discussed below.

Air emissions from natural gas combustion were taken from the GREET model (Reference A-116). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50). Since natural gas has a low sulfur and ash content, the sulfur dioxide and particulate emissions from natural gas emissions are very low when compared to other fossil fuels. The major pollutants from the burning of natural gas are nitrogen oxides. Nitrogen oxides are usually controlled by adjusting the firing parameters of a boiler.

No data are available for waterborne emissions from industrial boilers. Waterborne emissions do not result from the combustion-side of industrial boilers, but they do result from ancillary processes such as cooling water systems and boiler cleaning operations (Reference A-67). Since natural gas is a clean burning fuel, this appendix assumes that the cleaning of natural gas boilers is rare and thus produces negligible waterborne emissions (Reference A-95).

Solid waste emissions from fossil fuel combustion result from wastes from environmental controls (particulate and desulfurization controls) and bottom ash. Natural gas is a clean burning fuel with virtually no sulfur or particulate emissions. Thus, desulfurization and particulate controls are not employed for natural gas combustion. Also, due to its low ash content, natural gas combustion produces virtually no bottom ash or other solid wastes (Reference A-72). Thus, this appendix assumes that negligible solid wastes result from the combustion of natural gas in industrial boilers.

Industrial Equipment. Natural gas is used to power industrial equipment, including compressors used for pipeline transportation of natural gas. The calculations and assumptions used for estimating the environmental emissions associated with the combustion of natural gas in industrial equipment are discussed below.

Air emissions from natural gas combustion were taken from the GREET model (Reference A-116). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-96). Since natural gas has a low sulfur and ash content, the sulfur dioxide and particulate emissions from natural gas emissions are very low when compared to other fossil fuels.

Since natural gas has a low sulfur and ash content, it is a clean-burning fuel. This appendix thus assumes that the combustion of natural gas in industrial equipment produces negligible waterborne or solid waste emissions (References A-67 and A-95).

Combustion emissions for burning natural gas in utility and industrial boilers and in industrial equipment are shown in Table A-18. Precombustion emissions are calculated in the LCI model based on fuel production emissions shown in Tables A-1a through A-5, fuel combustion emissions shown in Tables A-14 through A-24, and precombustion fuel use shown in Table A-11.

Table A-18

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN BOILERS AND INDUSTRIAL EQUIPMENT (pounds of pollutants per 1,000 cubic feet of natural gas)

	Utility Boiler	Industrial Boiler	Industrial Equipment
Atmospheric Emissions			
Particulates (PM10)	0.0075	0.0072	0.0067
Particulates (PM2.5)	0.0075	0.0072	0.0067
Nitrogen Oxides	0.15	0.078	0.28
VOC (unspecified)	0.0046	0.0055	0.0022
Sulfur Oxides	5.8E-04	5.8E-04	5.8E-04
Carbon Monoxide	0.062	0.076	0.057
Fossil CO2	129	128	129
Aldehydes (Formaldehyde)	7.5E-05	7.5E-05	7.5E-05
Methane	0.0024	0.0024	0.0092
Arsenic	2.0E-07	2.0E-07	2.0E-07
Beryllium	1.2E-08	1.2E-08	1.2E-08
Cadmium	1.1E-06	1.1E-06	1.1E-06
Chromium (unspecified)	1.4E-06	1.4E-06	1.4E-06
Cobalt	8.4E-08	8.4E-08	8.4E-08
Lead	5.0E-07	5.0E-07	5.0E-07
Manganese	3.8E-07	3.8E-07	3.8E-07
Mercury	2.6E-07	2.6E-07	2.6E-07
Nickel	2.1E-06	2.1E-06	2.1E-06
Selenium	2.4E-08	2.4E-08	2.4E-08
Nitrous Oxide	0.0024	0.0024	0.0032
Benzene	2.1E-06	2.1E-06	2.1E-06
Naphthalene	6.1E-07	6.1E-07	6.1E-07
Radionuclides (unspecified)	2.6E-09	2.6E-09	2.6E-09

References: A-67, A-71, A-86, A-88, A-95, and A-116.

Source: Franklin Associates, A Division of ERG

Diesel

Industrial Equipment. Diesel is used in a wide variety of industrial applications such as mobile refrigeration units, generators, pumps, and portable well-drilling equipment. The calculations and assumptions used for estimating the environmental emissions from diesel combustion in industrial equipment are discussed below.

Air emissions for diesel combustion were taken from the GREET model (Reference A-116). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-97).

Diesel-powered industrial equipment does not employ particulate or sulfur control equipment, nor does it rely on flows of cooling water or steam (Reference A-95). It is thus assumed that the combustion of diesel in industrial equipment produces no solid waste or waterborne emissions.

Combustion emissions for burning diesel oil in industrial equipment are shown in Table A-19. Precombustion emissions are calculated in the LCI model based on fuel production emissions shown in Tables A-1a through A-5, fuel combustion emissions shown in Tables A-14 through A-24, and precombustion fuel use shown in Table A-12b.

Table A-19

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DIESEL FUEL IN INDUSTRIAL EQUIPMENT (pounds of pollutants per 1,000 gallons of diesel fuel)

Atmospheric Emissions	
Particulates (PM10)	25.3
Particulates (PM2.5)	22.8
Nitrogen Oxides	250
VOC (unspecified)	27.9
Sulfur Oxides	2.27
Carbon Monoxide	130
Fossil CO2	21,831
Aldehydes (Formaldehyde)	0.16
Aldehydes (Acetaldehyde)	0.11
Methane	1.11
Acrolein	0.013
Nitrous Oxide	0.57
Benzene	0.13
1,3 Butadiene	0.0054
Propylene	0.36
Toluene	0.057
Xylenes	0.040
Polyaromatic Hydrocarbons (total)	0.023

References: A-97 and A-116.

Source: Franklin Associates, A Division of ERG

Gasoline

Industrial Equipment. Gasoline is used in a wide variety of industrial applications such as mobile refrigeration units, generators, pumps, and portable well-drilling equipment. The calculations and assumptions used for estimating the environmental emissions from gasoline combustion in industrial equipment are discussed below.

Air emissions for gasoline combustion were taken from the GREET model (Reference A-116). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-97).

Gasoline-powered industrial equipment does not employ particulate or sulfur control equipment, nor does it rely on flows of cooling water or steam (Reference A-95). It is thus assumed that the combustion of gasoline in industrial equipment produces no solid waste or waterborne emissions.

Combustion emissions for burning gasoline in industrial equipment are shown in Table A-20. Precombustion emissions are calculated in the LCI model based on fuel production emissions shown in Tables A-1a through A-5, fuel combustion emissions shown in Tables A-14 through A-24, and precombustion fuel use shown in Table A-12c.

Table A-20

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF GASOLINE IN INDUSTRIAL EQUIPMENT
(pounds of pollutants per 1,000 gallons of gasoline)

Atmospheric Emissions	
Particulates (PM10)	9.16
Particulates (PM2.5)	8.43
Nitrogen Oxides	158
VOC (unspecified)	37.8
Sulfur Oxides	0.32
Carbon Monoxide	176
Fossil CO2	19,248
Aldehydes (Formaldehyde)	0.15
Aldehydes (Acetaldehyde)	0.096
Methane	1.89
Acrolein	0.012
Nitrous Oxide	0.61
Benzene	0.12
1,3 Butadiene	0.0049
Propylene	0.32
Toluene	0.051
Xylenes	0.057
Polyaromatic Hydrocarbons (total)	0.021

References: A-97 and A-116.

Source: Franklin Associates, A Division of ERG

Liquefied Petroleum Gases

Industrial Equipment. Liquefied petroleum gas (LPG) consists of propane, butane, or a mixture of the two. This gas is obtained both from natural gas liquids plants and as a byproduct of petroleum refinery operations. LPG is used in industrial boilers. The calculations and assumptions used for estimating the environmental emissions from LPG combustion in industrial boilers are discussed below.

Air emissions for LPG combustion were taken from the GREET model (Reference A-116). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-95).

LPG is a clean-burning fuel and produces neglible ash and sulfur oxide emissions (References A-67 and A-95). This eliminates the need for post-combustion control equipment and reduces the frequency at which combustion equipment is cleaned. It is thus assumed that LPG combustion produces no solid waste or waterborne emissions.

Combustion emissions for burning LPG in industrial equipment are shown in Table A-21. Precombustion emissions are calculated in the LCI model based on fuel production emissions shown in Tables A-1a through A-5, fuel combustion emissions shown in Tables A-14 through A-24, and precombustion fuel use shown in Table A-12d.

Table A-21

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF LIQUEFIED PETROLEUM GAS IN INDUSTRIAL BOILERS (pounds of pollutants per 1,000 gallons of LPG)

Atmospheric Emissions	
Particulates (PM10)	0.61
Particulates (PM2.5)	0.61
Nitrogen Oxides	13.4
VOC (unspecified)	0.35
Carbon Monoxide	3.44
Fossil CO2	12,728
Methane	0.20
Nitrous Oxide	0.91

References: A-116.

Source: Franklin Associates, A Division of ERG

Fuel Grade Uranium

Nuclear energy accounted for 19.8 percent of the total megawatt hours produced by U.S. electric utilities in 2000 (Reference A-62). Nuclear utilities generate electricity by harnessing the thermal energy from controlled nuclear fission reactions. These reactions are used to produce steam, which in turn drives a turbine-generator to produce electricity.

The quantity of uranium fuel (UO_2) consumed per kilowatt-hour of electricity production was calculated by comparing the quantity of uranium fuel loaded into U.S. nuclear reactors to the kilowatt-hours of electricity produced by U.S. nuclear reactors. From 1999 through 2001, an annual average of 54.3 million pounds of uranium concentrate (U_3O_8) was used to produce uranium fuel (UO_2) used in U.S. nuclear reactors (Reference A-103). During the same time period, an annual average of 750 billion kilowatt-hours of electricity was generated by U.S. nuclear reactors (Reference A-93). Using a conversion of 10.89 pounds of uranium concentrate per production of 1 pound of uranium fuel (Reference A-94), 0.0067 pounds of uranium fuel are required for the production of 1,000 kilowatt-hours of electricity.

Unlike utilities that require a daily or hourly supply of fuel (such as coal-fired utilities), the fuel for nuclear reactors does not need to be continuously recharged. A fuel load in a nuclear reactor can last up to three years (Reference A-60).

No data are available for the environmental emissions associated with the consumption of uranium fuel by nuclear power plants. Nuclear fission reactions are carefully controlled and spent nuclear fuel is encapsulated, so it is assumed that negligible environmental emissions result directly from uranium consumption. The ancillary processes in a nuclear power plant, including cooling water and steam generation processes, may result in environmental emissions. However, on the basis of the quantity of fuel consumed per unit of electrical output (Reference A-60), the extent of such emissions are also assumed to be negligible.

There are no direct combustion emissions for the use of uranium to produce electricity. Precombustion emissions are calculated in the LCI model based on fuel production emissions shown in Tables A-1a through A-5, fuel combustion emissions shown in Tables A-14 through A-24, and precombustion fuel use shown in Table A-13.

Wood Wastes

The combustion of wood in boilers is mostly confined to industries where it is available as a byproduct. It is burned to obtain both heat energy and to alleviate possible solid waste disposal problems. In boilers, wood is normally burned in the form of hogged wood, sawdust, shavings, chips, sander dust, or wood trim. Heating values for wood waste range from 4,000 to 5,000 Btu per pound of fuel on a wet, as-fired basis. The moisture content of as-fired wood is typically near 50 percent, but may vary from 5 to 75 weight percent.

Bark is the major type of waste burned in pulp mills; either a mixture of wood and bark waste or wood waste alone is burned most frequently in the lumber, furniture, and plywood industries. As of 1980, there were approximately 1,600 wood-fired boilers operating in the U.S., with a total capacity of over 30 GW (1.0 x 1011 Btu per hour).

The emission factors for this appendix are based on wet, as-fired wood waste with average properties of 50 percent (by weight) moisture and 4,500 Btu per pound higher heating value (Reference A-99).

Solid waste from the combustion of wood are proportional to the ash content of the wood. This typically varies between 0.5 and 2.2 percent by weight of dry wood. Some is released as flyash, and some remains as bottom ash. If there are controls for particulate matter, some of the flyash is collected before leaving the emissions stack.

The solid residues from the combustion process are boiler ash, clinker and slag, fly ash, and carbon char. The major components of these wastes are silica, alumina, and calcium oxides. Minor constituents include sodium, magnesium, potassium, and trace amounts of heavy metals (Reference A-98). Another source of solid wastes is impurities in wood bark (sand and dirt), which are picked up during transportation as rough logs are dragged to central loading points.

Emissions for the combustion of wood in industrial boilers are shown in Table A-22.

Table A-22

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF WOOD IN INDUSTRIAL BOILERS
(pounds of pollutant per 1,000 lb of wood—as fired)

	Combustion (lb/1000 lb)	Combustion (lb/MM Btu) (1)
Atmospheric Emissions		
Particulates (PM10)	2.25	0.50
Nitrogen Oxides	0.99	0.22
TNMOC (unspecified)	0.018	0.0041
Sulfur Oxides	0.11	0.025
Carbon Monoxide	2.70	0.60
Non-Fossil CO2	878	195
Aldehydes (Formaldehyde)	0.020	0.0044
Aldehydes (Acetaldehyde)	0.0037	8.3E-04
Methane	0.095	0.021
Chlorine	0.0036	7.9E-04
HCl	0.086	0.019
Metals (unspecified)	0.19	0.043
Antimony	3.6E-05	7.9E-06
Arsenic	9.9E-05	2.2E-05
Beryllium	5.0E-06	1.1E-06
Cadmium	1.8E-05	4.1E-06
Chromium (unspecified)	9.5E-05	2.1E-05
Cobalt	2.9E-05	6.5E-06
Lead	2.2E-04	4.8E-05
Manganese	0.0072	0.0016
Mercury	1.6E-05	3.5E-06
Nickel	1.5E-04	3.3E-05
Selenium	1.3E-05	2.8E-06
acrolein	0.018	0.0040
Nitrous Oxide	0.059	0.013
Benzene	0.019	0.0042
Naphthalene	4.4E-04	9.7E-05
Methylene Chloride	0.0013	2.9E-04
Carbon Tetrachloride	2.0E-04	4.5E-05
Phenols	2.3E-04	5.1E-05
dioxins (unspecified)	7.5E-06	1.7E-06
Waterborne Emissions		
BOD	8.75	1.94
Solid Waste	44.1	9.80

(1) Wood "as fired" has a higher heating value of about 4,500 Btu/lb.
References: A-57, A-98, A-99, A-118, and A-119.

Source: Franklin Associates, A Division of ERG

Mobile Sources

Transportation sources such as barges, locomotives, and diesel- and gasoline-powered trucks constitute a major source of air pollution. Some of the emissions, such as carbon monoxide and hydrocarbons, are due to incomplete combustion. Other emissions, such as nitrogen oxides, are normal byproducts of combustion. Lead emissions are directly related to the addition of tetraethyl lead to the fuel as an antiknock compound. Lead emissions have been decreasing significantly due to EPA regulations requiring a phase-out of lead in fuels. The major gaseous pollutants from mobile sources are carbon monoxide, nitrogen oxides, and hydrocarbons.

Trucks. Trucks are classified into two categories. Combination trucks (or tractor-trailer trucks) are those most commonly used for transporting large quantities of material. Single-unit trucks are generally used for local delivery. Several assumptions and calculations were made based on these classifications:

1. Single-unit delivery trucks have a gross weight of 8,500 to 14,000 pounds. Combination trucks include all trucks greater than 14,000 pounds in gross weight.

2. The average fuel economy for combination trucks is 5.3 miles per gallon. The average fuel economy for single-unit trucks is 7.4 miles per gallon (Reference A-100).

3. The majority (82 percent) of combination trucks use diesel, while a smaller percentage (18 percent) use gasoline (Reference A-101). Due to highly-aggregated statistics, an accurate split between diesel and gasoline use could not be determined for single-unit trucks. It was thus assumed that 50 percent of single unit trucks use diesel and 50 percent use gasoline.

4. Accounting for empty backhauling and trucks that are not fully loaded increases fuel usage by approximately 25 percent (Reference A-90).

Air emissions for gasoline- and diesel-powered trucks were taken from the GREET model (Reference A-116). Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference 12). The GREET transportation model includes data for most modes of transportation, but does not have emissions data for combination or single-unit trucks that use gasoline. Emissions for gasoline trucks were estimated based on the corresponding diesel truck emissions adjusted using the emissions ratio for gasoline and diesel reciprocating engines.

Locomotives. Freight locomotives use diesel fuel exclusively (Reference A-85). According to 2001 data, freight locomotives consume 2.48 gallons of diesel per ton-mile. This fuel requirement factor was calculated from the annual quantity of fuel consumed by freight locomotives and the annual ton-miles traveled by freight locomotives (Reference A-102).

Air emissions from diesel combustion in locomotives were taken from the GREET model (Reference A-116). Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50).

Barges. Commercial water transport can be categorized by boundary of travel, type of fuel consumed, and type of power source. The following details were used to develop an environmental profile for residual oil-powered barges:

1. Barges are typically vessels traveling in the Great Lakes, rivers, or along a coast. Ocean freighters encompass longer travel not within the range or capability of a barge.

2. Two types of engine technologies can be used as a power source for water vessels: diesel fuel engines and steam turbines using residual oil.

3. 22 percent of barges use diesel fuel in their engines, and 78 percent use residual oil to generate steam for steam turbines (Reference A-89).

4. The fuel requirements for a barge that consumes only residual oil are 3.4 gallons per 1,000 ton-miles (Reference A-89).

5. Power usage of the engines is 50 percent of full capacity. This adjusts for emissions occurring at dockside while the engine is idling.

Air emissions from residual and diesel fuel oil combustion in barges were taken from the GREET model (Reference A-116). Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50).

Ocean Freighters. Commercial water transport can be categorized by boundary of travel, type of fuel consumed, and type of power source. The following details were used to develop an environmental profile for ocean freighters:

1. Barges are typically vessels traveling in the Great Lakes, rivers, or along a coast. Ocean freighters are used for long distances not within the range or capability of a barge.

2. Two types of engine technologies can be used as a power source for water vessels: diesel fuel engines and steam turbines using residual oil.

3. 10 percent of ocean freighters use diesel fuel, and 90 percent use residual fuel. (Reference A-104).

4. The fuel requirements for an ocean freighter are 1.9 gallons of fuel per 1,000 ton-miles (Reference A-104). This value is assumed to be the same for diesel and residual oil.

5. Power usage of the engines is 50 percent of full capacity. This adjusts for emissions occurring at dockside while the engine is idling.

Air emissions from residual and diesel fuel oil combustion in ocean freighters were taken from the GREET model (Reference A-116). Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50).

Cargo Plane. The emissions from jet fuel combustion depend on the composition of the fuel, the type of engine, and the operating conditions of the engine. Jet fuel is similar to the kerosene, so this appendix assumes that jet fuel has the same composition as kerosene.

The types of jet engines currently in operation in commercial widebody jets were determined from data published by the Aviation Industry Press (Reference A-108). These data were used to develop a profile of the manufacturers and engine types that dominate the commercial widebody aircraft market. The conditions of airplane operation include takeoff and landing (TOL), cruising, and idle phases. Measured emissions for these conditions are available in the ICAO Engine Exhaust Data Bank (Reference A-107). The above data and assumptions were used to calculate the primary emissions (hydrocarbons, carbon monoxide, and nitrogen oxides) resulting from the combustion of jet fuel in widebody cargo planes.

Aviation emissions also include small amounts of sulfur oxides. No data are available for sulfur oxide emissions from jet engines. Since jet fuel contains less than 0.5 percent sulfur (Reference A-109), this module assumes that sulfur oxide emissions from aircraft are negligible. Aviation emissions also include particulates and trace amounts of metals; however, no data are available quantifying particulate or metal emissions from jet engines.

Tables A-23 and A-24 present combustion emissions for all transportation modes discussed in this appendix. Precombustion emissions are calculated in the LCI model based on fuel production emissions shown in Tables A-1a through A-5, fuel combustion emissions shown in Tables A-14 through A-24, and precombustion fuel use shown in Tables A-12b through A-12c and A-12e.

Table A-23

ENVIRONMENTAL EMISSIONS FOR COMBUSTION OF LAND TRANSPORTATION FUELS
(pounds of pollutants per 1,000 gallons of fuel)

	Tractor-Trailer Truck Diesel	Single-Unit Truck Diesel	Tractor-Trailer Truck Gasoline	Single-Unit Truck Gasoline	Locomotive Diesel
VOC	9.53	9.08	12.9	12.3	22.2
Carbon Monoxide	50.6	32.9	68.5	44.5	60.4
NOx	104	83.9	65.7	53.1	489
PM10	2.13	2.24	0.77	0.81	14.5
PM2.5	1.96	2.06	0.73	0.76	13.1
SOx	0.16	0.16	0.022	0.022	31.9
Methane	0.44	0.43	0.75	0.74	1.11
Nitrous Oxide	0.57	0.82	0.61	0.89	0.57
Fossil CO2	22,014	22,044	19,410	19,436	21,958

References: A-116.

Source: Franklin Associates, A Division of ERG

Table A-24

ENVIRONMENTAL EMISSIONS FOR COMBUSTION OF
MARINE AND AIR TRANSPORTATION FUELS
(pounds of pollutants per 1,000 gallons of fuel)

	Barge Residual	Barge Diesel	Ocean Residual	Ocean Diesel	Air Kerosene
VOC	12.0	11.0	28.8	26.4	
Carbon Monoxide	32.0	29.3	130	119	87.6
NOx	324	297	795	727	107
PM10	8.05	7.36	26.8	24.6	
PM2.5	4.02	3.68	20.1	18.4	
SOx	82.6	2.27	463	2.27	
Methane	0.59	0.54	1.42	1.30	
Nitrous Oxide	0.62	0.57	0.62	0.57	
Fossil CO2	26,213	22,043	26,004	21,852	20,903
Hydrocarbons (unspecified)					20.8

References: A-107, A-108, A-116.

Source: Franklin Associates, A Division of ERG

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GLOSSARY

Ash. Impurities in coal, consisting of silica, alumina, and other non-combustible matter. Ash increases the weight of coal, adds to the cost of handling, and can affect its burning characteristics.

Barrel (Petroleum). A unit of volume equal to 42 U.S. gallons.

Biological Oxygen Demand (BOD). An indication of the amount of organic material present in water or wastewater.

Biomass. The total dry organic matter or stored energy content of living organisms that is present at a specific time in a defined unit of the Earth's surface.

Bituminous Coal. A dense black coal, often with well-defined bands of bright and dull material, with a moisture content usually less than 20 percent. Often referred to as soft coal. It is the most common coal and is used primarily for generating electricity, making coke, and space heating.

Boiler. A device for generating steam for power, processing, or heating purposes or for producing hot water for heating purposes or hot water supply.

Btu (British Thermal Unit). A standard unit for measuring the quantity of heat energy equal to the quantity of heat required to raise the temperature of 1 pound of water by 1 degree Fahrenheit.

Butane. A normally gaseous straight-chained or branched hydrocarbon (C_4H_{10}). It is extracted from natural gas or refinery gas streams. It includes isobutane and normal butane.

Coal. A black or brownish-black solid, combustible substance formed by the partial decomposition of vegetable matter without access to air. The rank of coal, which includes anthracite, bituminous coal, subbituminous coal, and lignite, is based on fixed carbon, volatile matter, and heating value. Coal rank indicates the progressive alteration, or coalification, from lignite to anthracite.

Combustion Energy. The high heat value directly released when coal, fuel oil, natural gas, or wood are burned for energy consumption.

Combustion Emissions. The environmental emissions directly emitted when coal, fuel oil, natural gas, or wood are burned for energy consumption.

Crude Oil. A mixture of hydrocarbons that exists in liquid phase in underground reservoirs and remains liquid at atmospheric pressure after passing through surface separating facilities.

Curie (Ci). The SI unit of radioactive decay. The quantity of any radioactive nuclide which undergoes 3.7×10^{10} disintegrations/sec.

Distillate Fuel Oil. A general classification for one of the petroleum fractions produced in conventional distillation operations. It is used primarily for space heating, on-and off-highway diesel engine fuel (including railroad engine fuel and fuel for agricultural machinery), and electric power generation. Included are products known as No. 1, No. 2, and No. 4 diesel fuels.

Fossil Fuel. Any naturally occurring organic fuel, such as petroleum, natural gas, or coal.

Fossil Fuel Steam-Electric Power Plant. An electricity generation plant in which the prime mover is a turbine rotated by high-pressure steam produced in a boiler by heat from burning fossil fuels.

Flue Gas Desulfurization Unit (Scrubber). Equipment used to remove sulfur oxides from the combustion gases of a boiler plant before discharge to the atmosphere. Chemicals, such as lime, are used as the scrubbing media.

Fugitive Emissions. Unintended leaks of gas from the processing, transmission, and/or transportation of fossil fuels.

Geothermal Energy. Energy from the internal heat of the earth, which may be residual heat, friction heat, or a result of radioactive decay. The heat is found in rocks and fluids at various depths and can be extracted by drilling and/or pumping.

Heat Content of a Quantity of Fuel, Gross. The total amount of heat released when a fuel is burned. Coal, crude oil, and natural gas all include chemical compounds of carbon and hydrogen. When those fuels are burned, the carbon and hydrogen combine with oxygen in the air to produce carbon dioxide and water. Some of the energy released in burning goes into transforming the water into steam and is usually lost. The amount of heat spent in transforming the water into steam is counted as part of gross heat but is not counted as part of net content. Also referred to as the higher heating value. Btu conversion factors typically used by EIA represent gross heat content. Called combustion energy in this appendix.

Heat Content of a Quantity of Fuel, Net. The amount of usable heat energy released when a fuel is burned under conditions similar to those in which it is normally used. Also referred to as the lower heating value. Btu conversion factors typically used by EIA represent gross heat content.

Hydrocarbons: A subcategory of organic compounds which contain only hydrogen and carbon. These compounds may exist in either the gaseous, liquid, or solid phase, and have a molecular structure that varies from the simple to the very heavy and very complex. The category Non-Methane Hydrocarbons (NMHC) is sometimes used when methane is reported separately.

Hydroelectric Power Plant. A plant in which the turbine generators are driven by falling water.

Lease Condensate. A natural gas liquid recovered from gas well gas (associated and non-associated) in lease separators or natural gas field facilities. Lease condensate consists primarily of pentanes and heavier hydrocarbons.

Lignite. A brownish-black coal of low rank with a high content of moisture and volatile matter. Often referred to as brown coal.

Liquefied Petroleum Gases (LPG). Ethane, ethylene, propane, propylene, normal butane, butylene, isobutane, and isobutylene produced at refineries or natural gas processing plants, including plants that fractionate raw natural gas plant liquids.

Methane. A hydrocarbon gas (CH_4) that is the principal constituent of natural gas.

(**Motor) Gasoline.** A complex mixture of relatively volatile hydrocarbons, with or without small quantities of additives, that has been blended to form a fuel suitable for use in spark-ignition engines. "Motor gasoline" includes reformulated gasoline, oxygenated gasoline, and other finished gasoline.

Natural Gas. A mixture of hydrocarbons (principally methane) and small quantities of various nonhydrocarbons existing in the gaseous phase or in solution with crude oil in underground reservoirs.

Natural Gas Liquids (NGL). Those hydrocarbons in natural gas that are separated as liquids from the gas. Natural gas liquids include natural gas plant liquids (primarily ethane, propane, butane, and isobutane), and lease condensate (primarily pentanes produced from natural gas at lease separators and field facilities.)

Nitrogen Oxides (NO_X). Compounds of nitrogen and oxygen produced by the burning of fossil fuels, or any other combustion process taking place in air. The two most important oxides in this category are nitrogen oxide (NO) and nitrogen dioxide (NO_2). Nitrous oxide (N_2O), however, is not included in this category and is considered separately.

Non-Methane Volatile Organic Compounds. Organic compounds, other than methane, that participate in atmospheric photochemical reactions.

Other Organics. Compounds containing carbon combined with hydrogen and other elements such as oxygen, nitrogen, sulfur or others. Compounds containing only carbon and hydrogen are classified as hydrocarbons and are not included in this category.

Particulate Matter (Particulates): Small solid particles or liquid droplets suspended in the atmosphere, ranging in size from 0.005 to 500 microns.

Particulates are usually characterized as primary or secondary. Primary particulates, usually 0.1 to 20 microns in size, are those injected directly into the atmosphere by chemical or physical processes. Secondary particulates are produced as a result of chemical reactions that take place in the atmosphere. In our reports, particulates refer only to primary particulates.

Particulates reported by Franklin Associates are not limited by size range, and are sometimes called total suspended particulates (TSP). The category PM-10 refers to all particulates less than 10 microns in (aerodynamic) diameter. This classification is sometimes used when health effects are being considered, since the human nasal passages will filter and reject any particles larger than 10 microns.

Precombustion Energy. The energy required for the production and processing of energy fuels, such as coal, fuel oil, natural gas, or uranium, starting with their extraction from the ground, up to the point of delivery to the customer.

Precombustion Fuel-Related Emissions. The environmental emissions due to the combustion of fuels used in the production and processing of the primary fuels; coal, fuel oil, natural gas, and uranium.

Precombustion Process Emissions. The environmental emissions due to the production and processing of the primary fuels; coal, fuel oil, natural gas, and uranium, that are process rather than fuel-related emissions.

Petroleum. A generic term applied to oil and oil products in all forms, such as crude oil, lease condensate, unfinished oils, petroleum products, natural gas plant liquids, and nonhydrocarbon compounds blended into finished petroleum products.

Plant Condensate. One of the natural gas liquids (NGLs), mostly pentanes and heavier hydrocarbons, recovered and separated as liquids at gas inlet separators or scrubbers in processing plants.

Processing Plant (Natural Gas). A surface installation designed to separate and recover natural gas liquids from a stream of produced natural gas through the process of condensation, absorption, refrigeration, or other methods, and to control the quality of natural gas marketed or returned to oil or gas reservoirs for pressure maintenance, repressuring, or cycling.

Refinery (Petroleum). An installation that manufactures finished petroleum products from crude oil, unfinished oils, natural gas liquids, other hydrocarbons, and alcohol.

Residual Fuel Oil. The heavier oils that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. Included are No. 5, No. 6, and Navy Special. It is used for commercial and industrial heating, electricity generation, and to power ships.

Subbituminous Coal. A dull, black coal of rank intermediate between lignite and bituminous coal.

Sulfur Oxides (SO_X). Compounds of sulfur and oxygen, such as sulfur dioxide (SO_2) and sulfur trioxide (SO_3).

Total Dissolved Solids (TDS). The TDS in water consists of inorganic salts, minute organic particles, and dissolved materials. IN natural waters, salts are chemical compounds composed of anions such as carbonates, chlorides, sulfates, and nitrates, and cations such as potassium, magnesium, calcium, and sodium.

Total Suspended Solids (TSS). TSS gives a measure of the turbidity of the water. Suspended solids cause the water to be milky or muddy looking due to the light scattering from very small particles in the water.

Volatile Organic Compounds (VOCs). Organic compounds that participate in atmospheric chemical reactions.

Uranium. A heavy naturally radioactive metallic element (atomic number 92). Its two principally occurring isotopes are ^{235}U and ^{238}U. ^{235}U is indispensable to the nuclear industry, because it is the only isotope existing in nature to any appreciable extent that is fissionable by thermal neutrons. ^{238}U is also important, because it absorbs neutrons to produce a radioactive isotope that subsequently decays to ^{239}Pu, an isotope that also is fissionable by thermal neutrons.

Uranium Ore. Rock containing uranium mineralization, typically 0.05 to 0.2 percent U_3O_8.

APPENDIX B

DRINKING WATER DELIVERY SYSTEMS AND SUPPORTING PROCESSES

INTRODUCTION

The details for the scenarios of the analysis are presented in this appendix. The analysis has three baseline scenarios: (1) disposable single-serving containers filled by water bottlers, (2) reusable single-serving containers filled with tap water, and (3) reusable single-serving containers filled with HOD (home and office delivery) water from 5-gallon reusable containers. A figure with flow diagrams illustrating the life cycle stages for each system is presented at the end of this appendix.

SCENARIO 1: DISPOSABLE SINGLE-SERVING CONTAINERS

Scenario 1 includes several types of disposable single-serving containers, including: (1) PET bottles, (2) PLA (polylactic acid) bottles, and (3) glass bottles. The analysis includes evaluations of variations in container weight as well as evaluation of PET bottles with recycled content.

The average weight of 16.9-ounce PET containers was based on several samples obtained and weighed in the Kansas City area from 2007 to 2009, a sample obtained and weighed by Oregon DEQ in 2009, and current and future bottle weights for major producers of bottled water including Nestle, Coke, and Pepsi reported in a March 24, 2009 Wall Street Journal article. PET bottle weight data are shown in Table B-1a.

All bottles used plastic screw-cap closures made of polypropylene (PP).[2] Secondary packaging, which in this analysis is defined as corrugated boxes or trays and plastic stretch wrap used for the distribution of filled containers, is included in this scenario. Weights for three case packaging scenarios – a corrugated tray with film overwrap, a flat corrugated pad with film overwrap, and an all-film wrap – are presented in Table B-1a.

This scenario includes the municipal treatment and distribution of drinking water to bottlers, followed by additional water treatment and bottling operations. This scenario also includes the extraction of natural spring or well water, followed by water treatment and bottling operations. Bottlers who distribute water extracted from natural springs or wells are generally close to the site of water extraction, and thus the transportation requirements for distributing filled bottles are different for spring and well water than for water from municipal sources. Data for the treatment and pipeline distribution of municipal water are provided in Appendix E, and data for the treatment and filling activities at bottlers are provided in Appendix F.

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2 One glass bottle of carbonated water had an aluminum cap; however, this analysis does not include carbonated water, so the glass bottle closure was modeled based on the PP closure that was used on a glass bottle of non-carbonated bottled water.

This scenario assumes that disposable single-serving containers are used once and then discarded. For PET and glass bottles, end-of-life management includes a split between disposal (using landfill or combustion) and recycling. For PLA bottles, end-of-life management includes disposal (using landfill or combustion) and composting. Details on waste management are provided in Appendix J.

Disposable single serving containers may be refrigerated before consumption. Data for the energy requirements for the refrigeration of water are provided in Appendix H.

Based on the many parameters that can be varied in the single-use water bottle scenario (container material, recycled content, container weight, source of water, etc.), there are hundreds of potential combinations of variables that could be evaluated under Scenario 1. Table B-1b illustrates the input parameters that can be varied simultaneously. Additional variations in underlying processes such as bottle fabrication energy and filling energy may be evaluated during the sensitivity analysis phase of the project.

Table B-1a
MATERIALS AND WEIGHTS FOR DISPOSABLE SINGLE-SERVING WATER CONTAINERS
(grams per single container)

	PET Bottle (1)	**PLA Bottle (2)**	**Glass Bottle (3)**
Container volume in mL	500	500	357
Container volume in fluid ounces	16.9	16.9	12.1
Drinking Container			
PET		0	0
Aquafina (Franklin sample 2007)	12.6		
Nestle (Franklin sample 2009)	12.9		
EartH2O (DEQ sample 2009)	20.1		
Nestle regional (Wall St. Journal 3/09)	12.4		
Nestle Pure Life (Wall St. Journal 3/09)	11.0		
Coke Dasani (Wall St. Journal 3/09)	12.8		
Pepsi (Wall St. Journal 3/09)	13.7		
Pepsi Eco-Fina (Wall St. Journal 3/09)	10.9		
Average	**13.3**		
PET lightweight (Nestle Pure Life in 2011; Wall St. Journal)	9.8		
PET Fiji (4) (Franklin sample 2007)	27.5		
PLA	0	14.2	0
Glass	0	0	242
Closure			
Polypropylene	1.6	1.6	13.5
Secondary Packaging (5)			
Option 1			
Corrugated tray	3.83		
Film overwrap	1.23		
Option 2			
Corrugated pad	2.20		
Film overwrap	1.54		
Option 2			
Film overwrap	1.45		
Average of 3 options			
Corrugated	2.01	2.01	2.01
Stretch wrap	1.41	1.41	1.41
Subtotal: Container	00.0	14.2	242
Subtotal: Closure	1.60	1.60	13.50
Subtotal: Secondary packaging	3.42	3.42	3.42
TOTAL	**05.0**	**19.2**	**259**

(1) Weights based on Franklin Associates' sampling of bottled water and associated packaging purchased from retailers and PET bottle weight information from 3/24/09 Wall Street Journal article on most current weights of 500 ml PET water bottles.
(2) Based on similar water bottle studies by Franklin Associates, PLA bottles weigh approximately 3.3% more than PET bottles of the same size.
(3) Glass bottle weight is the average of two samples obtained and weighed by Franklin Associates in 2009.
(4) Because of the heavier weight of this bottle and the small percentage of U.S. bottled water that is imported, this weight is not used in the calculation of the average PET bottle weight; it is used only for the corresponding scenario for imported bottled water.
(5) Weight of secondary packaging per bottle based on samples of case packaging for 24-packs of 16.9-ounce bottled water. Options 1 and 2 obtained and weighed by Franklin Associates, option 3 obtained and weighed by DEQ. No multi-packs of non-carbonated water packaged in glass bottles were found, so the LCI modeling assumes that the amount of corrugated and film packaging required per glass bottle of water is similar to the amount used for plastic bottles.

References: B-1 through B-4

Source: Franklin Associates, A Division of ERG

Table B-1b
MODELING OPTIONS FOR SINGLE-USE BOTTLES

	Enter 1 to select ctr type	container wt in grams	Enter container vol in fl oz	Enter % recycled content
PET				
PLA				
Glass				

SOURCE AND TREATMENT OF WATER IN BOTTLE

Location for Water Processing & Filling

miles to OR distrib.

Oregon
Other US location
France (only for glass)
Fiji

Water in bottle (enter 1 to select natural or purified municipal)

Natural Municipal

Water processing steps (enter 1 for each process used)

Natural Municipal

Reverse osmosis
Ozone
Ultraviolet

FILLING AND DISTRIBUTION - SINGLE-USE BOTTLES

If plastic bottle is molded off-site, enter information on transport to filler

Miles transported

Enter 1 if bottles rinsed before filling

Packaging of filled bottles for shipment

bottles/case

Store to consumer

Miles store to home by personal vehicle
Gro trip allocation to purchasing water

CHILLING (optional)

Chilling of bottled water (indiv bottles)

days chilled

Chilling method

Home refrigeration
Commercial refrigeration

RECYCLING OF EMPTY CONTAINERS

Postconsumer recovery rate

PET bottle recovery
Glass bottle recovery
PLA bottle composting
PLA bottle recycling (placeholder - no data available at this time)
Corrugated packaging recovery

PLA % decomposition in landfill

Recycling allocation method (enter method number)

1 Open-loop (shared burdens)
2 No disposal burdens for bottles that are recovered for recycling
3 Production & disposal burdens for recycled material passed on to user system

SCENARIO 2: REUSABLE SINGLE-SERVING CONTAINERS FILLED WITH TAP WATER

Scenario 2 includes sub-scenarios for reusable single-serving containers filled with municipal drinking water (tap water). Four types of drinking containers are included in this scenario: (1) plastic containers, (2) aluminum containers, (3) stainless steel containers, and (4) an open-top glass tumbler. In order to most closely match the portability that is an inherent characteristic of bottled water, the reusable containers used for consumption of tap and HOD water were selected to include several types of containers widely used for away-from-home consumption of water. The sizes of the different material containers were based on popular brands of each container. The plastic, aluminum, and steel containers have a plastic screw-top closure that makes them appropriate for on-the-go use. The glass tumbler does not have a closure and is not suitable for on-the-go use, but can be used in home or office settings. The materials and weights of the reusable single-serving containers are summarized in Table B-2a.

Table B-2a
MATERIALS AND WEIGHTS FOR REUSABLE SINGLE-SERVING WATER CONTAINERS THAT ARE FILLED WITH TAP WATER
(grams per single container)

	Plastic container (1)	Aluminum container (2)	Steel container (3)	Glass tumbler (4)
Container volume in mL	946	591	798	473
Container volume in fluid ounces	32.0	20.0	27.0	16.0
Drinking Container				
Polyester copolymer	104	0	0	0
Aluminum	0	100	0	0
Stainless steel	0	0	227	0
Glass tumbler (no lid)	0	0	0	184
Closure				
Polypropylene	18.0	12.5	36.9	0
Subtotal: Container	104	100	227	184
Subtotal: Closure	18.0	12.5	36.9	0
TOTAL	**122**	**113**	**264**	**184**

(1) Based on weights provided on website of a container producer (www.nalgen-outdoor.com/technical/weights.html). Accessed September 2008.
(2) Weight of aluminum container based on data provided by SIGG container, SIGG SWITZERLAND AG, August 2008.
(3) Based on correspondence between Franklin Associates and Kleen Kanteen, August 2008.
(4) Measurement of glassware by Franklin Associates, September 2008.

References: B-1 through B-4.

Source: Franklin Associates, A Division of ERG

This scenario includes the treatment and distribution of municipal drinking water Municipal drinking water is distributed by pipeline. Data for municipal drinking water treatment and distribution are provided in Appendix E.

If used daily over a period of one to five years, reusable single-serving containers may be used from several hundred to over 1,000 times. The number of uses is a parameter that will be included in the LCI models, and the effect that this parameter has on the LCI results will be determined. The reusable single-serving containers are washed in residential dishwashers. The number of times the container is washed is a parameter that will be included in the LCI models, and the effect that this parameter has on the LCI results will be determined. Data for the energy requirements and water use of residential dishwashers are provided in Appendix I.

Reusable plastic containers have commonly been made from polycarbonate; however, due to recent questions about the potential health effects of bisphenol-A, a chemical used in the production of polycarbonate, new types of plastics are being used as substitutes for polycarbonate. According to a contact at Eastman Chemical Company, polyester copolymers are being used; however, no data on the production of these copolymers is available. They are modeled in this analysis as PET.

After being used many times, reusable containers are eventually discarded. The copolyester used in reusable containers for personal use uses resin identification code 7 and therefore would not be recycled with other PET containers at end of life (Reference B-8). Although glass packaging is accepted in Oregon recycling programs, glassware such as drinking glasses is not; therefore, drinking glasses would also be disposed. Aluminum containers and stainless steel containers can be recycled. Data for end-of-life waste management are provided in Appendix J. Because the weight of one container is small, and the burdens for each container will be divided over hundreds of lifetime uses, end-of-life management of discarded reusable containers will be included only if the quantity of material allocated to the functional unit is large enough to influence results. This will be determined in the modeling and sensitivity analysis phase.

Tap water in reusable containers may be consumed chilled or unchilled. If chilled, consumers may use refrigerated water or add ice cubes to cool the water. This scenario includes sub-scenarios that employ refrigeration or ice cubes for cooling water before consumption. Data for refrigeration and ice cubes are provided in Appendix H.

Home filtration is not included in the scope of this study. Home filtration systems consist of a unit attached to the tap with a filter that is replaced periodically. Because these filtration systems do not consume energy and many gallons of water are filtered before a filters is replaced, it is expected that the impacts of home filtration would be very small when expressed on the basis of 1,000 gallons of water.

Based on the many parameters that can be varied in the reusable container scenario (container material, container weight, reuses per container, frequency of washing, etc.), there are hundreds of potential combinations of variables that could be evaluated under Scenario 2. Table B-2b illustrates the input parameters that can be varied simultaneously. Additional variations in underlying processes such as container fabrication energy and dishwasher operation will be evaluated during the sensitivity analysis phase of the project.

Table B-2b
MODELING OPTIONS FOR REUSABLE CONTAINERS FILLED WITH TAP WATER

	Enter 1 to select ctr type	Enter container wt in grams	Enter container vol in fl oz	Enter times filled per day	Enter years of use
Virgin aluminum					
Stainless steel					
PET					
Glass tumbler					

Drinking water used to fill primary reusable container (enter 1 to select)

	Tap
	5-gal HOD

Frequency of washing is calculated based on number of ounces consumed from container before washing

	days of use before container is washed
	low water wash
	high water wash

CHILLING (optional)
For tap water

	days chilled

Chilling method

	Refrigerator chilling in 1/2 gal pitcher		
	Ice		ice as volume % of water

RECYCLING OF EMPTY CONTAINERS

Postconsumer recovery rate

	Recycling of metal reusable container

Recycling allocation method (enter method number)

	1	Open-loop (shared burdens)
	2	No disposal burdens for bottles that are recovered for recycling
	3	Production & disposal burdens for recycled material passed on to user system

SCENARIO 3: REUSABLE SINGLE-SERVING CONTAINERS FILLED WITH HOD WATER

Scenario 3 includes sub-scenarios for reusable single-serving containers filled with water delivered in 5-gallon HOD containers. The reusable containers evaluated in Scenario 3 are identical to those in Scenario 2; the only difference between Scenarios 2 and 3 is the source of the water used to fill the container (tap vs. HOD container). Five-gallon HOD containers may be produced from polycarbonate, PET, or a polyester copolymer; the most commonly used materials are polycarbonate and PET. The materials and weights of the reusable single-serving containers and HOD containers are summarized in Table B-3a. Although only one 5-gallon HOD container was weighed by

Franklin Associates for this study, the representativeness of this container weight was confirmed by other HOD bottlers.

Table B-3a
MATERIALS AND WEIGHTS FOR REUSABLE SINGLE-SERVING WATER CONTAINERS THAT ARE FILLED WITH HOD WATER
(grams per single container)

	Plastic container (1)	Aluminum container (2)	Steel container (3)	Glass tumbler (4)
Container volume in mL	946	591	798	473
Container volume in fluid ounces	32.0	20.0	27.0	16.0
Drinking Container				
Polyester copolymer	104	0	0	0
Aluminum	0	100	0	0
Stainless steel	0	0	227	0
Glass tumbler (no lid)	0	0	0	184
Closure	0	0	0	0
Polypropylene	18.0	12.5	36.9	0
Subtotal: Container	104	100	227	184
Subtotal: Closure	18.0	12.5	36.9	0
TOTAL	**122**	**113**	**264**	**184**
HOD Container (5 gallon) (5,6)				
Polycarbonate or PET	750	750	750	750

(1) Based on weights provided on website of a container producer (www.nalgen-outdoor.com/technical/weights.html). Accessed September 2008.
(2) Weight of aluminum container based on data provided by SIGG container, SIGG SWITZERLAND AG, August 2008.
(3) Based on correspondence between Franklin Associates and Kleen Kanteen, August 2008.
(4) Measurement of glassware by Franklin Associates, September 2008.
(5) Based on Franklin Associates' measurement of 5-gallon HOD water container. According to a confidential industry contact, approximately 90% of HOD containers are polycarbonate and 10% are PET.
(6) The number of times a container is filled for 5-gallons of water consumption is not accounted for in this table. Such a factor depends on the number of times a consumer uses a container; this is a scenario to be evaluated in the LCI model.

References: B-5 through B-7.

Source: Franklin Associates, A Division of ERG

The number of lifetime uses of the HOD bottles and reusable containers have a much greater influence on the material requirements per thousand gallons of water compared to variations in the container bottle weight, e.g., due to manufacturer variations or future lightweighting. It should be noted that the container weights in Tables B-2a and B-3a have *not* been adjusted to account for the number of lifetime uses of the container.

Table B-3a shows only the weights of each single-serving container and a 5-gallon HOD container. A consumer could fill a single, 12-ounce glass 53 times from a 5-gallon HOD container. Alternatively, the same consumer could fill 53, 12-ounce glasses one time per glass from a 5-gallon HOD container. The number of times a consumer fills a glass (or other type of single serving container) with water from an HOD container is a scenario that will be accounted for in the LCI model.

As in Scenario 2, a range of reuse rates and washing rates will be evaluated for the reusable container, and the effect of these variations on LCI results will be determined. Data for the energy requirements and water use of residential dishwashers are provided in Appendix I.

This scenario assumes that reusable 5-gallon containers are used between 20 and 40 times. As with single-serving container, the number of uses for 5-gallon containers is a parameter that will be included in the LCI models, and the effect that this parameter has on the LCI results will be determined. Five-gallon containers are collected and washed as part of the HOD supply chain. Data for the energy requirements and water use associated with the collection and washing of 5-gallon containers are provided in Appendix I.

This scenario includes the municipal treatment and distribution of drinking water to bottlers, followed by additional water treatment and filling of 5-gallon containers for HOD. This scenario also includes the extraction and transport of natural spring or well water, followed by water treatment and filling of 5-gallon containers for HOD. Data for the treatment and distribution of drinking water are provided in Appendix E, and data for the treatment and filling activities at bottlers are provided in Appendix F.

The water in 5-gallon containers is cooled by stand-alone water coolers, which chill and dispense water. Data for the energy requirement of water coolers are provided Appendix H.

End-of-life management of reusable individual drinking containers is discussed in the previous section. According to a representative of an HOD bottler (Reference B-9), when five-gallon HOD containers (including those made from PET and polycarbonate) can no longer be used for water delivery, they are sold to plastics recyclers. Data for end-of-life waste management are provided in Appendix J.

Based on the many parameters that can be varied in Scenario 3, (e.g., container material, container weight, reuses per container, HOD bottle material and reuse rate, etc.), there are hundreds of potential combinations of variables that could be evaluated under Scenario 3. Table B-3b illustrates the input parameters that can be varied simultaneously. Additional variations in underlying processes such as HOD bottle fabrication energy, filling, and washing processes may be evaluated during the sensitivity analysis phase of the project.

Table B-3b
MODELING OPTIONS FOR REUSABLE CONTAINERS FILLED WITH HOD WATER

	Enter 1 to select ctr type	Enter container wt in grams	Enter container vol in fl oz	Enter times filled per day	Enter years of use
Virgin aluminum					
Stainless steel					
PET					
Glass tumbler					

Drinking water used to fill primary reusable container (enter 1 to select)

	Tap
	5-gal HOD

Frequency of washing is calculated based on number of ounces consumed from container before washing

	days of use before container is washed
	low water wash
	high water wash

5-GAL HOD BOTTLE (if selected above)

	Enter 1 to select ctr type	Enter container wt in grams	Enter no. of trips before recycled
Polycarbonate bottle			
PET bottle			

Location for Water Processing & Filling

		miles to OR distrib.
	Oregon	
	Other US location	

Water in HOD bottle (enter 1 to select natural or purified municipal)

Natural	Municipal

Water processing steps (enter 1 for each process used)

Natural	Municipal	
		Reverse osmosis
		Ozone
		Ultraviolet

FILLING AND DISTRIBUTION - HOD BOTTLES

Route distribution (dropoff of filled containers & pickup of empties for refill)

	Round trip miles by truck (single-unit)

CHILLING (optional)

For HOD water

	HOD chiller unit

RECYCLING OF EMPTY CONTAINERS

Recycling allocation method (enter method number)

	1	Open-loop (shared burdens)
	2	No disposal burdens for bottles that are recovered for recycling
	3	Production & disposal burdens for recycled material passed on to user system

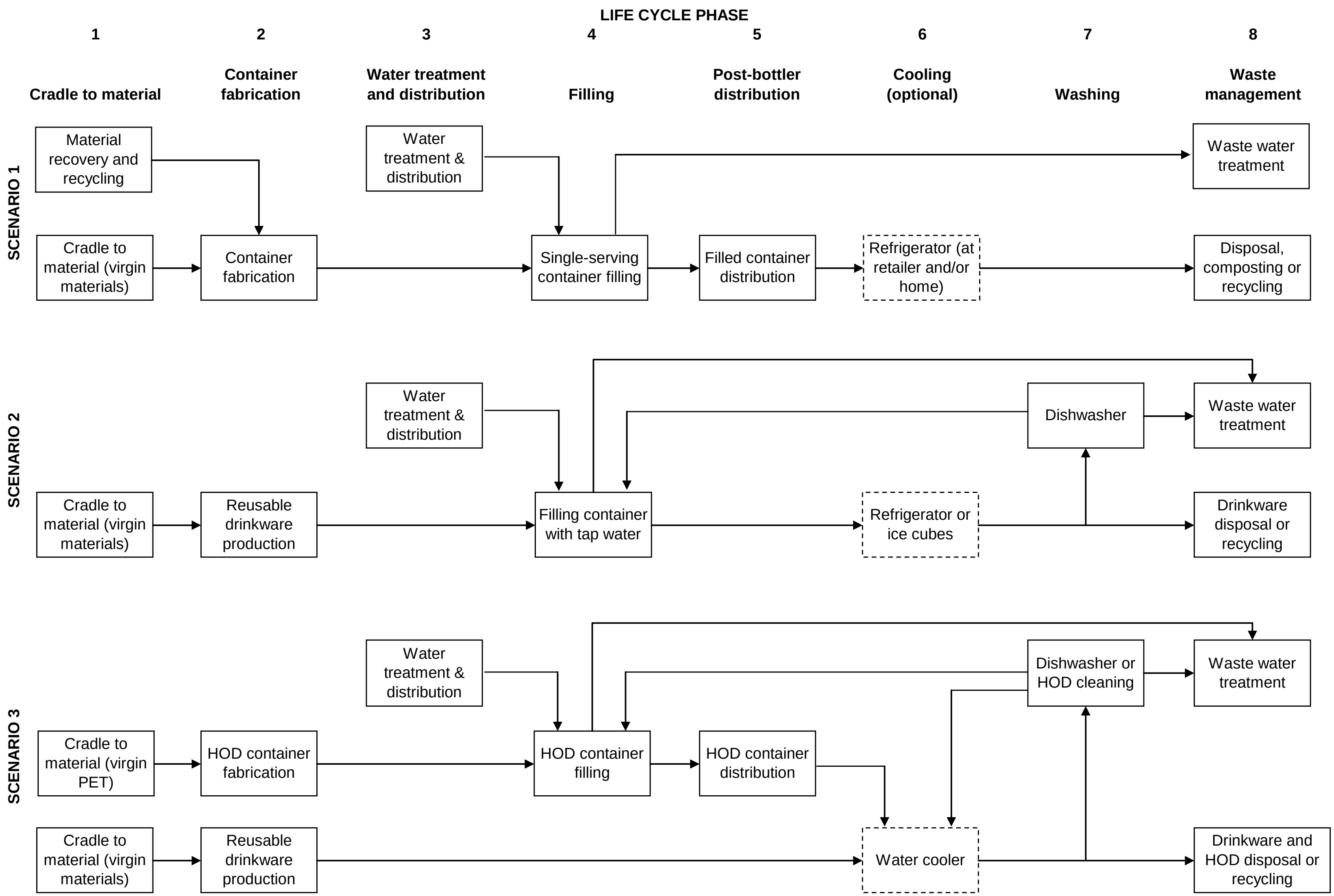


Figure B-1. Flow Diagrams for Three Baseline Scenarios.

REFERENCES

B-1 Samples of plastic and glass containers purchased at local retailers by Franklin Associates. September 2008.

B-2 Coca-Cola Enterprises 2007 Corporate Responsibility and Sustainability Report. Available at http://www.cokecce.com/assets/uploaded_files/2007_CRSReport.pdf.

B-3 Coca-Cola Aims to Increase Recycled Content, Reduce Weight of Bottles. GreenBizSite (http://www.greenbiz.com). July 25, 2008.

B-4 Franklin Associates estimate based on similar systems.

B-5 Correspondence between Franklin Associates and SIGG container, SIGG SWITZERLAND AG, August 2008.

B-6 Correspondence between Franklin Associates and Kleen Kanteen, August 2008.

B-7 Samples of plastic, 5-gallon containers provided to Franklin Associates by a local HOD (home and office delivery) facility.

B-8 Correspondence between Franklin Associates and Eastman Chemical Company, November 2008.

B-9 Discussion with representative of Hinckley Springs® water. September 2008.

B-10 Bauerlein, Valerie. "Pepsi to Pare Plastic for Bottled Water." Wall Street Journal. March 25, 2009.

APPENDIX C

MATERIAL PRODUCTION FOR DRINKING WATER CONTAINER SYSTEMS

INTRODUCTION

This appendix includes data for cradle-to-gate production of the materials used for drinking water containers and ancillary packaging. Information on the following materials is included in this appendix:

- HDPE (High Density Polyethylene)
- LDPE (Low Density Polyethylene)
- PP (Polypropylene)
- PET (Polyethylene Terephthalate)
- Polycarbonate
- Polyester Copolymer
- PLA (Polylactide)
- Glass
- Virgin (Primary) Aluminum
- Steel
- Corrugated Paperboard

The data in this appendix do not include fabrication processes (the activities of converting materials into containers or packaging). Data for the fabrication of containers and packaging are provided in Appendix D. Appendix J includes information on collection and recycling of postconsumer plastic, which may be used as a percentage of the input material for production of some containers.

HIGH-DENSITY POLYETHYLENE

Almost 16 billion pounds of HDPE was produced in the U.S. and Canada in 2003 (Reference C-107). The production of HDPE includes the following processes:

- Crude Oil Production
- Distillation, Desalting, and Hydrotreating
- Natural Gas Production
- Natural Gas Processing
- Olefins (Ethylene) Production
- HDPE Resin Production

The material flow for HDPE resin is shown in Figure C-1.

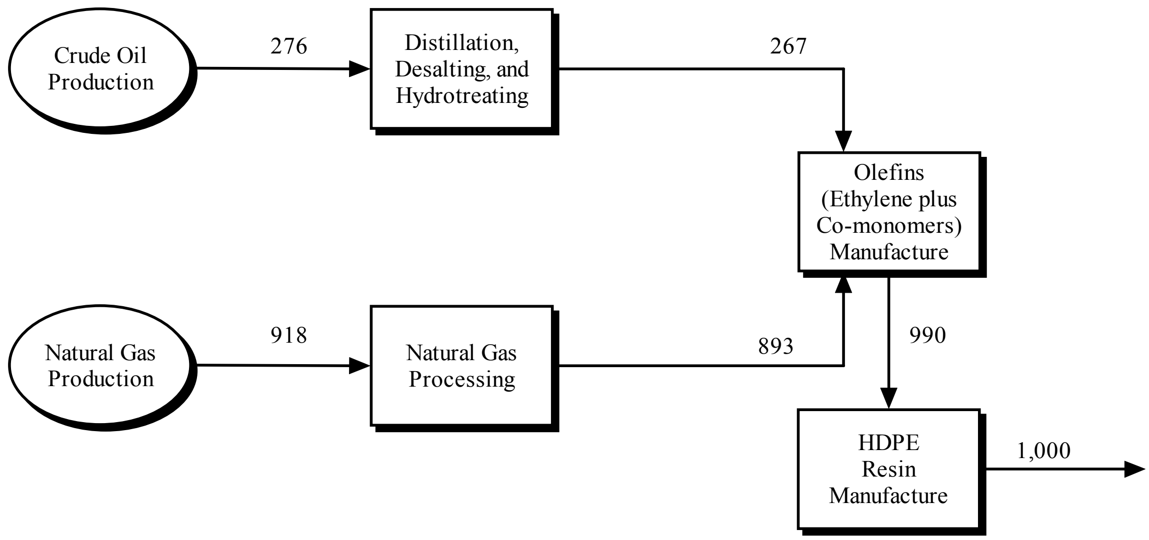


Figure C-1: Flow diagram for HDPE production

Crude Oil Production

Drilling into porous rock structures generally located several thousand feet underground produces oil. Once an oil deposit is located, numerous holes are drilled and lined with steel casing. Some oil is brought to the surface by natural pressure in the rock structure, although most oil requires energy to drive pumps that lift oil to the surface. Once oil is on the surface, it is separated from water and stored in tanks before being transported to a refinery. In some cases it is immediately transferred to a pipeline that transports the oil to a larger terminal.

There are two primary sources of waste from crude oil production. The first source is the “oil field brine,” or water that is extracted with the oil. The brine goes through a separator at or near the wellhead in order to remove the oil from the water. These separators are very efficient and leave minimal oil in the water.

According to the American Petroleum Institute, 17.9 billion barrels of brine water were produced from crude oil production in 1995 (Reference C-108). This equates to a ratio of 5.4 barrels of water per barrel of oil. The majority of this water (85 percent) is produced by onshore oil production facilities and, since such facilities are prohibited from discharging to surface water (Reference C-109), is injected into wells specifically designed for production-related waters. The remaining 15 percent of water discharges from offshore oil production facilities are assumed to be released to the ocean. Therefore, all waterborne wastes from crude oil production are attributable to the water released from offshore production (Reference C-110). Because crude oil is frequently produced along with natural gas, a portion of the waterborne waste is allocated to natural gas production (Reference C-108).

Evolving technologies are reducing the amount of brine that is extracted during oil recovery and minimizing the environmental impact of discharged brine. For example, downhole separation is a technology that separates brine from oil before bringing it to the surface; the brine is injected into subsurface injection zones. The freeze-thaw evaporation (FTE) process is another technology that reduces the discharge of brine water by using a freeze crystallization process in the winter and a natural evaporation process in the summer to extract fresh water from brine water; the fresh water can be used for horticulture or agriculture applications (Reference C-111).

The second source of waste is gas produced from oil wells. The majority of this gas is recovered for sale, but some is released to the atmosphere. Atmospheric emissions from crude oil production are primarily hydrocarbons. They are attributed to the natural gas produced from combination wells and relate to line or transmission losses and unflared venting. The amount of methane released from crude oil production was calculated from EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks, which has data specific to oil field emissions (Reference C-112).

The requirements for transporting crude oil from the production field to the Gulf Coast of the United States (where most petroleum refining in the United States occurs) were calculated from foreign and domestic supply data, port-to-port distance data, and domestic petroleum movement data (References C-113 and C-114). Based on 2001 foreign and domestic supply data, 62 percent of the United States crude oil supply is from foreign sources, 6 percent is from Alaska, and the remaining 32 percent is from the lower 48 states. These percentages were used to apportion transportation requirements among different transportation modes. With the exception of Canada, which transports crude oil to the United States by pipeline, foreign suppliers transport crude oil to the United States by ocean tanker. (In 2001, Saudi Arabia, Mexico, Canada, Venezuela, and Nigeria were the top five foreign suppliers of crude oil to the United States.) The transportation of crude oil from Alaska to the lower 48 states is also accomplished by ocean tanker. Domestic transportation of crude oil is accomplished by pipeline and barge.

Table C-1 shows the energy requirements and emissions for the extraction of crude oil.

Table C-1

DATA FOR THE EXTRACTION OF
1,000 POUNDS OF CRUDE OIL
(page 1 of 2)

Energy Usage			**Total Energy Thousand Btu**
Energy of Material Resource			
Petroleum	1,035	lb	19,538
Total Resource			19,538
Process Energy			
Electricity (grid)	17.7	kwh	188
Natural gas	525	cu ft	588
Distillate oil	0.15	gal	24.6
Residual oil	0.10	gal	16.4
Gasoline	0.082	gal	11.7
Total Process			829
Transportation Energy			
Barge	0.37	ton-miles	
Diesel	3.0E-04	gal	0.048
Residual oil	0.0010	gal	0.17
Ocean freighter	1,472	ton-miles	
Diesel	0.28	gal	44.4
Residual	2.52	gal	432
Pipeline-petroleum products	196	ton-miles	
Electricity	4.27	kwh	43.8
Total Transportation			520
Environmental Emissions			
Atmospheric Emissions			
Methane	3.53	lb	
Solid Wastes			
Landfilled	26.1	lb	
Waterborne Wastes			
1-Methylfluorene	4.0E-07	lb	
2,4-Dimethylphenol	1.0E-04	lb	
2-Hexanone	2.3E-05	lb	
2-Methylnaphthalene	5.6E-05	lb	
4-Methyl-2-Pentanone	1.5E-05	lb	
Acetone	3.6E-05	lb	
Alkylated benzenes	1.7E-04	lb	
Alkylated fluorenes	1.0E-05	lb	
Alkylated naphthalenes	2.9E-06	lb	
Alkylated phenanthrenes	1.2E-06	lb	
Aluminum	0.32	lb	
Ammonia	0.053	lb	
Antimony	2.0E-04	lb	
Arsenic	9.8E-04	lb	
Barium	4.36	lb	
Benzene	0.0060	lb	
Benzoic acid	0.0036	lb	
Beryllium	5.5E-05	lb	
BOD	0.62	lb	
Boron	0.011	lb	
Bromide	0.76	lb	
Cadmium	1.5E-04	lb	
Calcium	11.4	lb	
Chlorides	128	lb	
Chromium	0.0085	lb	
Cobalt	7.9E-05	lb	
COD	1.02	lb	
Copper	0.0010	lb	

Table C-1

DATA FOR THE EXTRACTION OF 1,000 POUNDS OF CRUDE OIL (page 2 of 2)

Cyanide	2.6E-07	lb
Dibenzofuran	6.8E-07	lb
Dibenzothiophene	5.5E-07	lb
Ethylbenzene	3.4E-04	lb
Fluorine	5.0E-06	lb
Hardness	35.2	lb
Hexanoic acid	7.5E-04	lb
Iron	0.63	lb
Lead	0.0021	lb
Lead 210	3.7E-13	lb
Lithium	0.0038	lb
Magnesium	2.23	lb
Manganese	0.0036	lb
Mercury	3.5E-06	lb
Methylchloride	1.4E-07	lb
Methyl Ethyl Ketone	2.9E-07	lb
Molybdenum	8.2E-05	lb
m-Xylene	1.1E-04	lb
Naphthalene	6.5E-05	lb
n-Decane	1.0E-04	lb
n-Docosane	3.8E-06	lb
n-Dodecane	2.0E-04	lb
n-Eicosane	5.4E-05	lb
n-Hexacosane	2.4E-06	lb
n-Hexadecane	2.1E-04	lb
Nickel	9.8E-04	lb
n-Octadecane	5.3E-05	lb
n-Tetradecane	8.6E-05	lb
o + p-Xylene	7.8E-05	lb
o-Cresol	1.0E-04	lb
Oil and grease	0.072	lb
p-Cresol	1.1E-04	lb
p-Cymene	3.6E-07	lb
Pentamethylbenzene	2.7E-07	lb
Phenanthrene	1.0E-06	lb
Phenol	0.0016	lb
Radium 226	1.3E-10	lb
Radium 228	6.6E-13	lb
Selenium	3.9E-05	lb
Silver	0.0075	lb
Sodium	36.2	lb
Strontium	0.19	lb
Sulfates	0.26	lb
Sulfur	0.0094	lb
Surfactants	0.0030	lb
Thallium	4.2E-05	lb
Tin	8.0E-04	lb
Titanium	0.0031	lb
Toluene	0.0056	lb
Total Alkalinity	0.28	lb
Total biphenyls	1.1E-05	lb
Total dibenzothiophenes	3.5E-08	lb
Total dissolved solids	158	lb
Total suspended solids	9.77	lb
Vanadium	9.7E-05	lb
Xylene	0.0028	lb
Yttrium	2.4E-05	lb
Zinc	0.0073	lb

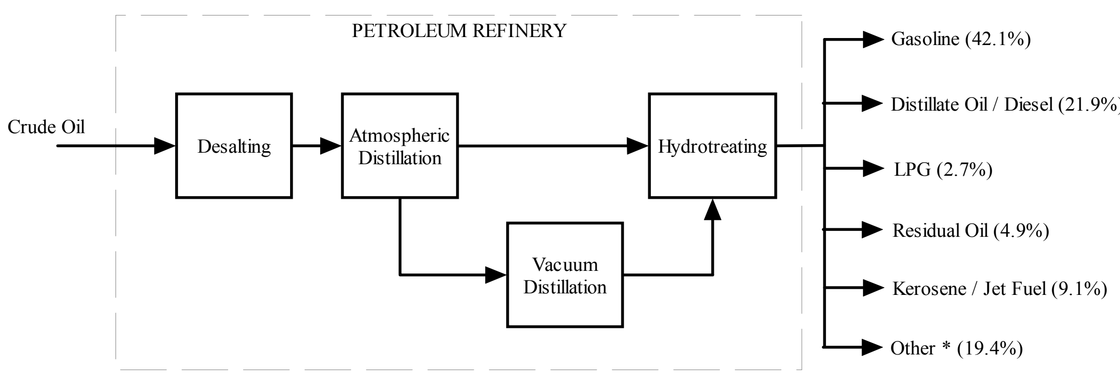
References: C-108, C-112, and C-114 through C-123

Source: Franklin Associates, A Division of ERG

Distillation, Desalting, and Hydrotreating

A petroleum refinery processes crude oil into thousands of products using physical and/or chemical processing technology. A petroleum refinery receives crude oil, which is comprised of mixtures of many hydrocarbon compounds and uses distillation processes to separate pure product streams. Because the crude oil is contaminated (to varying degrees) with compounds of sulfur, nitrogen, oxygen, and metals, cleaning operations are common in all refineries. Also, the natural hydrocarbon components that comprise crude oil are often chemically changed to yield products for which there is higher demand. These processes, such as polymerization, alkylation, reforming, and visbreaking, are used to convert light or heavy crude oil fractions into intermediate weight products, which are more easily handled and used as fuels and/or feedstocks (Reference C-124).

This module includes data for desalting, atmospheric distillation, vacuum distillation, and hydrotreating. These are the most energy-intensive processes of a petroleum refinery, representing over 95 percent of the total energy requirements of U.S. petroleum refineries (Reference C-125). Data for cracking, reforming, and supporting processes are not available and are not included in this module. Figure C-2 is a simplified flow diagram of the material flows and processes included in this module.



Simplified flow diagram for petroleum refinery operations for the production of fuels.
All arrows represent material flows. The percentages of refinery products represent percent by mass of total refinery output.
* "Other" category includes still gas, petroleum coke, asphalt, and petrochemical feedstocks.

Figure C-2: Key petroleum refinery processes and percent share of refined products

Air pollution is caused by various petroleum refining processes, including vacuum distillation, catalytic cracking, thermal cracking processes, and sulfur recovery. Fugitive emissions also contribute significantly to air emissions. Fugitive emissions include leaks from valves, seals, flanges, and drains, as well as leaks escaping from storage tanks or during transfer operations. The wastewater treatment plant for a refinery is also a source of fugitive emissions (Reference C-126).

This module expresses data on the basis 1,000 pounds of general refinery product as well as data allocated to specific refinery products. The data are allocated to specific refinery products based on the percent by mass of each product in the refinery output. The mass allocation method assigns energy requirements and environmental emissions equally to all refinery products -- equal masses of different refinery products are assigned equal energy and emissions.

Mass allocation is not the only method that can be used for assigning energy and emissions to refinery products. Heat of combustion and economic value are two additional methods for co-product allocation. Using heat of combustion of refinery products yields allocation factors similar to those derived by mass allocation, demonstrating the correlation between mass and heat of combustion. Economic allocation is complicated because market values fluctuate with supply and demand, and market data are not available for refinery products such as asphalt. This module does not apply the heat of combustion or economic allocation methods because they have no apparent advantage over mass allocation.

Co-product function expansion is yet another method for allocating environmental burdens among refinery products. Co-product function expansion is more complex than mass, heat of combustion, or economic allocation; it evaluates downstream processes and product substitutes in order to determine the percentage of total energy and emissions to assign to each refinery product. This module does not use the co-product function expansion method because it is outside the scope of this project.

There are advantages and disadvantages for each type of allocation method. Until detailed data are available for the material flows and individual processes within a refinery, life cycle practitioners will have to resort to allocation methods such as those discussed above.

The energy requirements and emissions for the refining of petroleum are found in Table C-2.

Table C-2

**DATA FOR THE REFINING OF
1,000 POUNDS OF PETROLEUM**

			Total Energy Thousand Btu
Raw Materials			
Crude Oil	1,034	lb	
Energy Usage			
Process Energy			
Electricity (grid)	64.9	kwh	691
Natural gas	178	cu ft	199
LPG	0.14	gal	14.9
Residual oil	3.26	gal	560
Total Process			1,465
Transportation Energy			
Combination truck	13.6	ton-miles	
Diesel	0.14	gal	22.8
Rail	8.70	ton-miles	
Diesel	0.02	gal	3.4
Barge	73.7	ton-miles	
Diesel	0.06	gal	9.4
Residual oil	0.20	gal	33.7
Pipeline-petroleum products	107	ton-miles	
Electricity	2.335	kwh	23.92
Total Transportation			93.1
Environmental Emissions			
Atmospheric Emissions			
Aldehydes	0.042	lb	
Ammonia	0.021	lb	
Carbon monoxide	13.3	lb	
Carbon tetrachloride	1.2E-08	lb	
CFC12	1.2E-07	lb	
Hydrocarbons (non-methane)	2.03	lb	
Methane	0.071	lb	
NOx	0.33	lb	
Particulates (unspecified PM)	0.24	lb	
SOx (unspecified)	2.35	lb	
Trichloroethane	9.7E-08	lb	
Solid Wastes			
Landfilled	5.60	lb	
Waterborne Wastes			
BOD5	0.034	lb	
COD	0.23	lb	
Chromium (hexavalent)	3.7E-05	lb	
Chromium (unspecified)	5.7E-04	lb	
Nitrogen (as ammonia)	0.015	lb	
Oil and Grease	0.011	lb	
Phenolic Compounds	2.3E-04	lb	
Sulfide	1.9E-04	lb	
Total Suspended Solids	0.028	lb	

References: C-112, C-122, C-123, and C-128 through C-132

Source: Franklin Associates, A Division of ERG

Natural Gas Production

Natural gas is a widely used energy resource, since it is a relatively clean, efficient, and versatile fuel. The major component of natural gas is methane (CH_4). Other components of natural gas include ethane, propane, butane, and other heavier hydrocarbons, as well as water vapor, carbon dioxide, nitrogen, and hydrogen sulfides.

Natural gas is extracted from deep underground wells and is frequently co-produced with crude oil. Because of its gaseous nature, natural gas flows quite freely from wells which produce primarily natural gas, but some energy is required to pump natural gas and crude oil mixtures to the surface. All natural gas production in this analysis is based on U.S. production, with an estimated 80 percent of natural gas extracted onshore and 20 percent extracted offshore (Reference C-118).

Atmospheric emissions from natural gas production result primarily from unflared venting. Waterborne wastes result from brines that occur when natural gas is produced in combination with oil. In cases where data represent both crude oil and natural gas extraction, the data module allocates environmental emissions based on the percent weight of natural gas produced. The data module also apportions environmental emissions according to the percent share of onshore and offshore extraction.

Energy data for natural gas production were calculated from fuel consumption data for the crude oil and natural gas extraction industry (Reference C-127). The energy and emissions data for the production of natural gas is displayed in Table C-3. No separate statistics were available on the transport of natural gas from extraction sites to processing sites; total transportation requirements for U.S. natural gas distribution are believed to be captured in the transportation statistics reported in Table C-4.

Table C-3

DATA FOR THE EXTRACTION OF
1,000 POUNDS OF NATURAL GAS
(page 1 of 2)

Energy Usage			**Total Energy Thousand Btu**
Energy of Material Resource			
Natural Gas	1,038	lb	23,265
Total Resource			23,265
Process Energy			
Electricity (grid)	17.7	kwh	188
Natural gas	525	cu ft	588
Distillate oil	0.15	gal	24.6
Residual oil	0.10	gal	16.4
Gasoline	0.082	gal	11.7
Total Process			829
Environmental Emissions			
Atmospheric Emissions			
Methane	11.9	lb	
Solid Wastes			
Landfilled	24.7	lb	
Waterborne Wastes			
1-Methylfluorene	4.9E-07	lb	
2,4-Dimethylphenol	1.2E-04	lb	
2-Hexanone	2.8E-05	lb	
2-Methylnapthalene	6.8E-05	lb	
4-Methyl-2-Pentanone	1.8E-05	lb	
Acetone	4.3E-05	lb	
Alkylated benzenes	4.2E-05	lb	
Alkylated fluorenes	2.4E-06	lb	
Alkylated naphthalenes	6.9E-07	lb	
Alkylated phenanthrenes	2.9E-07	lb	
Aluminum	0.079	lb	
Nitrogen (as ammonia)	0.053	lb	
Antimony	4.8E-05	lb	
Arsenic	9.5E-04	lb	
Barium	1.22	lb	
Benzene	0.0072	lb	
Benzoic acid	0.0044	lb	
Beryllium	4.3E-05	lb	
BOD	0.75	lb	
Boron	0.013	lb	
Bromide	0.92	lb	
Cadmium	1.4E-04	lb	
Calcium	13.8	lb	
Chlorides	155	lb	
Chromium (unspecified)	0.0022	lb	
Cobalt	9.5E-05	lb	
COD	1.24	lb	
Copper	6.1E-04	lb	
Cyanide	3.1E-07	lb	
Dibenzofuran	8.2E-07	lb	
Dibenzothiophene	6.6E-07	lb	
Ethylbenzene	4.1E-04	lb	
Fluorine	1.5E-06	lb	

Table C-3

DATA FOR THE EXTRACTION OF
1,000 POUNDS OF NATURAL GAS
(page 2 of 2)

Hardness	42.6	lb
Hexanoic acid	9.0E-04	lb
Iron	0.25	lb
Lead	0.0014	lb
Lead 210	4.5E-13	lb
Lithium	4.62	lb
Magnesium	2.70	lb
Manganese	0.0044	lb
Mercury	8.4E-07	lb
Methylchloride	1.7E-07	lb
Methyl Ethyl Ketone	3.5E-07	lb
Molybdenum	9.9E-05	lb
m-Xylene	1.3E-04	lb
Naphthalene	7.8E-05	lb
n-Decane	1.3E-04	lb
n-Docosane	4.6E-06	lb
n-Dodecane	2.4E-04	lb
n-Eicosane	6.5E-05	lb
n-Hexacosane	2.9E-06	lb
n-Hexadecane	2.6E-04	lb
Nickel	7.5E-04	lb
n-Octadecane	6.4E-05	lb
n-Tetradecane	1.0E-04	lb
o + p-Xylene	9.5E-05	lb
o-Cresol	1.2E-04	lb
Oil and grease	0.083	lb
p-Cresol	1.3E-04	lb
p-Cymene	4.3E-07	lb
Pentamethylbenzene	3.2E-07	lb
Phenanthrene	5.5E-07	lb
Phenolic compounds	0.0019	lb
Radium 226	1.6E-10	lb
Radium 228	8.0E-13	lb
Selenium	9.5E-06	lb
Silver	0.0090	lb
Sodium	43.8	lb
Strontium	0.23	lb
Sulfates	0.32	lb
Sulfur	0.011	lb
Surfactants	0.0043	lb
Thallium	1.0E-05	lb
Tin	4.7E-04	lb
Titanium	7.4E-04	lb
Toluene	0.0068	lb
Total Alkalinity	0.35	lb
Total biphenyls	2.7E-06	lb
Total dibenzothiophenes	8.4E-09	lb
Total dissolved solids	192	lb
TSS	2.73	lb
Vanadium	1.2E-04	lb
Xylene	0.0034	lb
Yttrium	2.9E-05	lb
Zinc	0.0021	lb

References: C-108, C-112, and C-114 through C-123

Source: Franklin Associates, A Division of ERG

Natural Gas Processing

Once raw natural gas is extracted, it is processed to yield a marketable product. First, the heavier hydrocarbons such as ethane, butane and propane are removed and marketed as liquefied petroleum gas (LPG). Then the water vapor, carbon dioxide, and nitrogen are removed to increase the quality and heating value of the natural gas. If the natural gas has a high hydrogen sulfide content, it is considered "sour." Before it is used, hydrogen sulfide is removed by adsorption in an amine solution—a process known as "sweetening."

Atmospheric emissions result from the flaring of hydrogen sulfide (H_2S), the regeneration of glycol solutions, and fugitive emissions of methane. Hydrogen sulfide is a natural component of natural gas and is converted to sulfur dioxide (SO_2) when flared; sulfur dioxide emissions were calculated from EPA emission factors (Reference C-132) and the known hydrogen sulfide content of domestic natural gas (Reference C-133). Glycol solutions are used to dehydrate natural gas, and the regeneration of these solutions result in the release of BTEX (benzene, toluene, ethylbenzene, and xylene) as well as a variety of less toxic organics (Reference C-134). Methane emissions result from fugitive releases as well as venting (Reference C-135). Negligible particulate emissions are produced from natural gas plants, and the relatively low processing temperatures (<1,200 degrees Fahrenheit) prevent the formation of nitrogen oxides (NOx).

Natural gas is transported primarily by pipeline, but a small percentage is compressed and transported by insulated railcars and tankers (References C-136 and C-137). Transportation data were calculated from the net annual quantities of natural gas imported and exported by each state (Reference C-138).

Energy data for natural gas processing were calculated from fuel consumption data for the natural gas liquids extraction industry (Reference C-115). Table C-4 shows the energy and emissions data for processing natural gas. Sulfur was given no coproduct allocation in this process. The amount of H_2S in the sour natural gas varies widely depending on where it is extracted.

Table C-4

**DATA FOR THE PROCESSING OF
1,000 POUNDS OF NATURAL GAS**

			Total Energy Thousand Btu
Raw Materials			
Natural gas	1,028	lb	
Energy Usage			
Process Energy			
Electricity (grid)	9.67	kwh	103
Natural gas	554	cu ft	620
Distillate oil	0.0060	gal	0.96
Residual oil	0.0059	gal	1.02
Gasoline	0.0057	gal	0.81
Total Process			726
Transportation Energy			
Combination truck	5.00	ton-miles	
Diesel	0.052	gal	8.33
Rail	5.00	ton-miles	
Diesel	0.012	gal	1.97
Pipeline-natural gas	500	ton-miles	
Natural gas	345	cu ft	386
Total Transportation			397
Environmental Emissions			
Atmospheric Emissions			
Benzene	0.10	lb	
Toluene	0.15	lb	
Ethylbenzene	0.012	lb	
Xylene	0.087	lb	
VOC	0.77	lb	
Sulfur Oxides	24.3	lb	
Methane	1.88	lb	

References: C-115 through C-118, C-123, C-132 through C-137, and C-39.

Source: Franklin Associates, A Division of ERG

Olefins Production (Ethylene)

The primary process used for manufacturing olefins is the thermal cracking of saturated hydrocarbons such as ethane, propane, naphtha, and other gas oils.

Typical production of ethylene, propylene, and other coproducts begins when hydrocarbons and steam are fed to the cracking furnace. After being heated to temperatures around 1,000° Celsius, the cracked products are quenched in heat exchangers which produce high pressure steam. Fuel oil is separated from the main gas stream in a multi-stage centrifugal compressor. The main gas stream then undergoes hydrogen sulfide removal and drying. The final step involves fractional distillation of the various reaction products.

A weighted average using production amounts was calculated from the olefins production data collected from three leading producers (8 thermal cracking units) in North America. Transportation amounts for ethylene were calculated using a weighted average of data collected from the polyethylene producers. Table C-5 shows the averaged energy and emissions data for the production of ethylene. Numerous coproduct streams are produced during this process. Fuel gas and off-gas were two of the coproducts produced; the energy amounts for these coproducts are reported separately as recovered energy. A mass basis was used to partition the credit for the remaining products.

As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. (Reference C-145). While data was collected from a relatively small sample of plants, the olefins producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American olefins production. The average dataset was reviewed and accepted by all olefins data providers.

To assess the quality of the data collected for olefins, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for olefins include direct measurements, information provided by purchasing and utility records, and estimates. The standard production technology for olefins is the steam cracking of hydrocarbons (including natural gas liquids and petroleum liquids). The data in this appendix represent steam cracking of natural gas and petroleum. All data submitted for olefins represent the year 2003 and U.S. and Canada production.

Table C-5

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF ETHYLENE

				Total Energy Thousand Btu
Raw Materials (1)				
Refined petroleum products	237	lb		
Processed natural gas	791	lb		
Additional Raw Materials used for Internal Energy (2)				
Refined petroleum products	115	lb		
Processed natural gas	112	lb		
Water Consumption	180	gal		
Energy Usage				
Process Energy				
Electricity (grid)	35.7	kwh		380
Electricity (cogeneration)	30.8	kwh		210
Natural gas	2,313	cu ft		2,591
Gasoline	0.011	gal		1.56
Diesel	0.010	gal		1.59
Recovered Energy	1,990	thousand Btu		(1,990)
Total Process (Net)				1,194
Transportation Energy				
Ethylene products				
Pipeline-petroleum products	60.0	ton-miles		
Electricity	1.31	kwh		13.4
Environmental Emissions				
Atmospheric Emissions				
Aldehydes	1.0E-07	lb	(3)	
Carbon Monoxide	0.056	lb		
Carbon Dioxide	1.00	lb	(3)	
Chlorine	1.0E-04	lb	(3)	
HCFC-022	1.0E-06	lb	(3)	
Hydrogen Chloride	1.0E-06	lb	(3)	
Hydrogen	0.0011	lb		
Hydrocarbons (NM)	0.053	lb		
Methane	0.017	lb		
Nitrogen Oxides	0.010	lb	(3)	
Nitrous Oxide	0.0010	lb	(3)	
Other Organics	0.0010	lb	(3)	
Particulates (unspecified)	0.0075	lb		
Particulates (PM2.5)	0.0010	lb	(3)	
Particulates (PM10)	0.047	lb		
Sulfur Oxides	0.023	lb		
VOC	0.010	lb	(3)	
Solid Wastes				
Landfilled	0.29	lb		
Burned	3.60	lb		
Waste-to-Energy	0.023	lb		
Waterborne Wastes				
Acetone	1.0E-09	lb	(3)	
Benzene	1.0E-05	lb	(3)	
BOD	4.1E-04	lb		
COD	0.010	lb	(3)	
Ethylbenzene	1.0E-05	lb	(3)	
Naphthalene	1.0E-09	lb	(3)	
Phenol	1.0E-04	lb	(3)	
Styrene	1.0E-07	lb	(3)	
Suspended Solids	0.0026	lb		
Toluene	1.0E-04	lb	(3)	
Total Organic Carbon	0.0010	lb	(3)	
Xylene	1.0E-07	lb	(3)	

(1) Specific raw materials from oil refining and natural gas processing include ethane, propane, liquid feed, heavy raffinate, and DNG.

(2) A portion of the material feed combusts within the hydrocracker, which provides an internal energy source.

(3) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

References: C-140, C-141, C-142, C-143, and C-144.

Source: Franklin Associates, A Division of ERG

High-Density Polyethylene Resin Production

High-density polyethylene is produced through the polymerization of ethylene. Polyethylene is manufactured by a slurry, solution, or a gas phase process. The average dataset includes data for the slurry and gas phase processes, which are discussed here. Ethylene and small amounts of co-monomers are continuously fed with a catalyst into a reactor.

In the slurry process, ethylene and co-monomers come into contact with the catalyst, which is suspended in a diluent. Particulates of polyethylene are then formed. After the diluent is removed, the reactor fluff is dried and pelletized.

In the gas phase process, a transition metal catalyst is introduced into a reactor containing ethylene gas, co-monomer, and a molecular control agent. The ethylene and co-monomer react to produce a polyethylene powder. The ethylene gas is separated from the powder, which is then pelletized.

A weighted average using production amounts was calculated from the HDPE production data from five plants collected from three leading producers in North America. The energy requirements and emissions data for the production of HDPE resin is displayed in Table C-6. Scrap is produced as a coproduct during this process. A mass basis was used to partition the credit for each product.

As of 2003, there were 10 HDPE producers and 23 HDPE plants in the U.S. (Reference C-146). While data was collected from a small sample of plants, the HDPE producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American HDPE production. The average dataset was reviewed and accepted by all HDPE data providers.

To assess the quality of the data collected for HDPE, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for HDPE include direct measurements, calculations from equipment specifications, information provided by purchasing and utility records, and estimates. The technology represented by the HDPE data represents a combination of UNIPOL gas and slurry processes. All data submitted for HDPE represent the year 2003 and U.S. and Canadian production. For purposes of this analysis, the transportation distance from the resin manufacturer to a converter was estimated as 500 miles by truck.

Table C-6

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF HIGH-DENSITY POLYETHYLENE (HDPE) RESIN

				Total Energy Thousand Btu
Raw Materials				
Olefins	990	lb		
Water Consumption	179	gal		
Energy Usage				
Process Energy				
Electricity (grid)	80.7	kwh		858
Electricity (cogeneration)	100	kwh		683
Natural gas	569	cu ft		637
LPG	0.0045	gal		0.49
Residual oil	0.72	gal		124
Total Process				2,302
Transportation Energy				
Combination truck	250	ton-miles		
Diesel	3	gal		417
Environmental Emissions				
Atmospheric Emissions				
Carbon Monoxide	0.16	lb		
Methane	0.014	lb		
Nitrogen Oxides	0.029	lb		
Hydrocarbons (NM)	0.42	lb		
Other Organics	0.010	lb	(1)	
Particulates (unknown)	0.018	lb		
PM2.5	0.012	lb		
PM10	0.041	lb		
Sulfur Oxides	4.8E-05	lb		
Solid Wastes				
Landfilled	0.36	lb		
Burned	0.26	lb		
Waste-to-Energy	0.0040	lb		
Waterborne Wastes				
Aluminum	0.0010	lb	(1)	
BOD	0.0056	lb		
COD	0.0010	lb	(1)	
Chlorides	1.0E-06	lb	(1)	
Chromium	1.0E-05	lb	(1)	
Dissolved solids	0.044	lb		
Furans	1.0E-06	lb	(1)	
Hydrocarbons	0.0010	lb	(1)	
Oil	0.0043	lb		
Phenol/Phenolics	1.0E-05	lb	(1)	
Phosphorus	1.0E-04	lb	(1)	
Process solvents	1.0E-04	lb	(1)	
Suspended solids	0.052	lb		
Zinc	8.5E-05	lb		

(1) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

References: C-141

Source: Franklin Associates, A Division of ERG

LOW-DENSITY POLYETHYLENE

Approximately 8 billion pounds of LDPE was produced in the U.S. and Canada in 2003 (Reference C-147). The production of LDPE includes the following processes:

- Crude Oil Production
- Distillation, Desalting, and Hydrotreating
- Natural Gas Production
- Natural Gas Processing
- Olefins (Ethylene) Production
- LDPE Resin Production

The material flows for LDPE resin production are shown in Figure C-3.

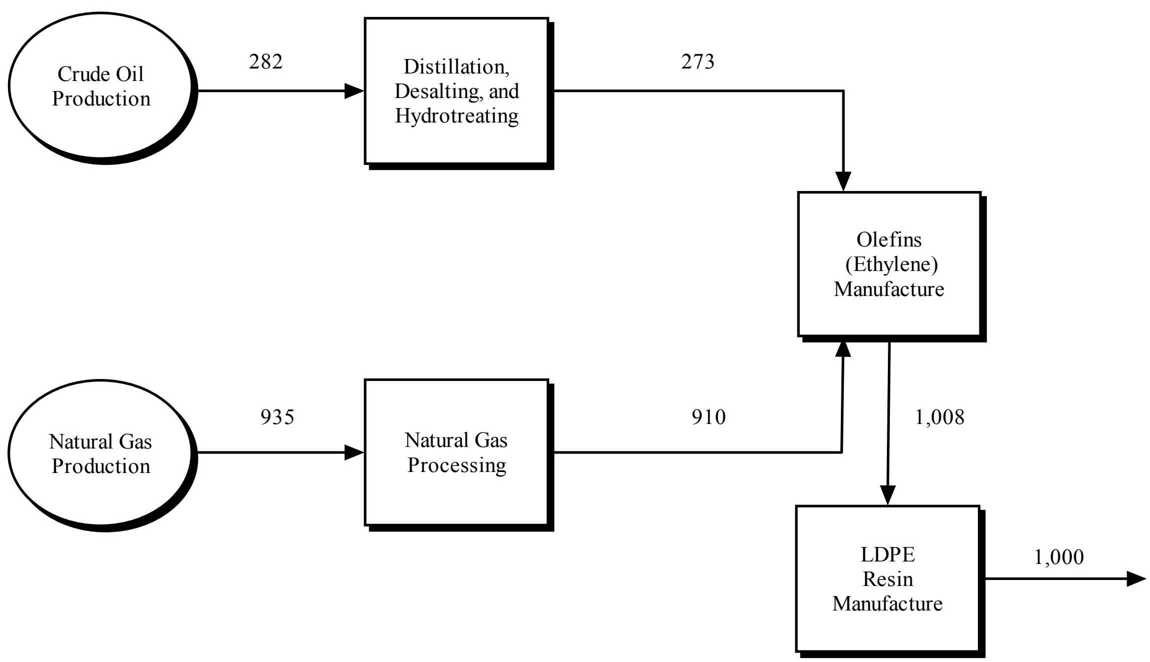


Figure C-3: Flow diagram for LDPE production

LDPE Resin Production

Low-density polyethylene (LDPE) is produced by the polymerization of ethylene in high pressure reactors (above 3,000 psi). This is the standard technology for LDPE production. The two reactor types used are autoclaves and tubular reactors. Generally, tubular reactors operate at a higher average ethylene conversion than autoclave reactors. The polymerization mechanism is either free-radical, using peroxide initiators, or ionic polymerization, using Ziegler catalyst.

Reactor effluent consists of unreacted ethylene and polymer. The pressure of the effluent mixture is reduced and the ethylene is purified and recycled back to the reactor.

A weighted average using production amounts was calculated from the LDPE production data from seven plants collected from three leading producers in North America. Table C-7 displays the energy and emissions data for the production of 1,000 pounds of LDPE resin. Scrap and steam are produced as coproducts during this process. A mass basis was used to partition the credit for scrap, while the energy amount for the steam was reported separately as recovered energy.

As of 2003, there were 8 LDPE producers and 15 LDPE plants in the U.S. (Reference C-149). The LDPE data collected for this module represents a majority of North American LDPE production. The average dataset was reviewed and accepted by all LDPE data providers.

To assess the quality of the data collected for LDPE, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for LDPE include direct measurements, information provided by purchasing and utility records, and estimates. The technology represented by the LDPE data represents a combination of the tubular and autoclave high-pressure reactors. All data submitted for LDPE represent the years 2002 and 2003 and production in U.S. and Canada. For purposes of this analysis, the transportation distance from the resin manufacturer to a converter was estimated as 500 miles by truck.

Table C-7

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF LOW-DENSITY POLYETHYLENE (LDPE) RESIN

				Total Energy Thousand Btu
Raw Materials				
Olefins	1,008	lb		
Water Consumption	499	gal		
Energy Usage				
Process Energy				
Electricity (grid)	85.5	kwh		909
Electricity (cogeneration)	328	kwh		2,242
Natural gas	609	cu ft		682
LPG	0.0038	gal		0.41
Residual oil	0.16	gal		27.4
Total Process				3,861
Transportation Energy				
Combination truck	250	ton-miles		
Diesel	3	gal		417
Environmental Emissions				
Atmospheric Emissions				
Carbon Monoxide	0.010	lb	(1)	
Carbon Dioxide	10.0	lb	(1)	
Chlorine	1.0E-06	lb	(1)	
HFC/HCFC	0.0010	lb	(1)	
Methane	0.0066	lb		
NM Hydrocarbons	0.87	lb		
Nitrogen Oxides	0.0010	lb	(1)	
Nitrous Oxide	0.0010	lb	(1)	
Other Organics	0.050	lb		
Particulates (unknown)	0.045	lb		
PM2.5	0.0055	lb		
PM10	0.026	lb		
Sulfur Oxides	1.0E-05	lb	(1)	
Solid Wastes				
Landfilled	0.063	lb		
Burned	0.24	lb		
Waterborne Wastes				
Aluminum	1.0E-04	lb	(1)	
BOD	0.010	lb	(1)	
COD	0.10	lb	(1)	
Dissolved Solids	0.0010	lb	(1)	
CFC-011	1.0E-04	lb	(1)	
Isopropyl Alcohol	1.0E-04	lb	(1)	
Oil	0.0010	lb	(1)	
Phenol/Phenolics	1.0E-06	lb	(1)	
Phosphorus	1.0E-04	lb	(1)	
Suspended Solids	0.010	lb	(1)	
Zinc	1.0E-05	lb	(1)	

(1) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

References: C-142

Source: Franklin Associates, A Division of ERG

POLYPROPYLENE

More than 17 billion pounds of PP was produced in the U.S. and Canada in 2003 (Reference C-150). The production of HDPE includes the following processes:

- Crude Oil Production
- Distillation, Desalting, and Hydrotreating
- Natural Gas Production
- Natural Gas Processing
- Propylene Production
- Polypropylene Resin Production

Crude oil production, distillation, desalting, and hydrotreating, natural gas production, and natural gas processing are discussed in previously in the appendix and are not repeated in this section.

The material flows for polypropylene resin production are shown in Figure C-4.

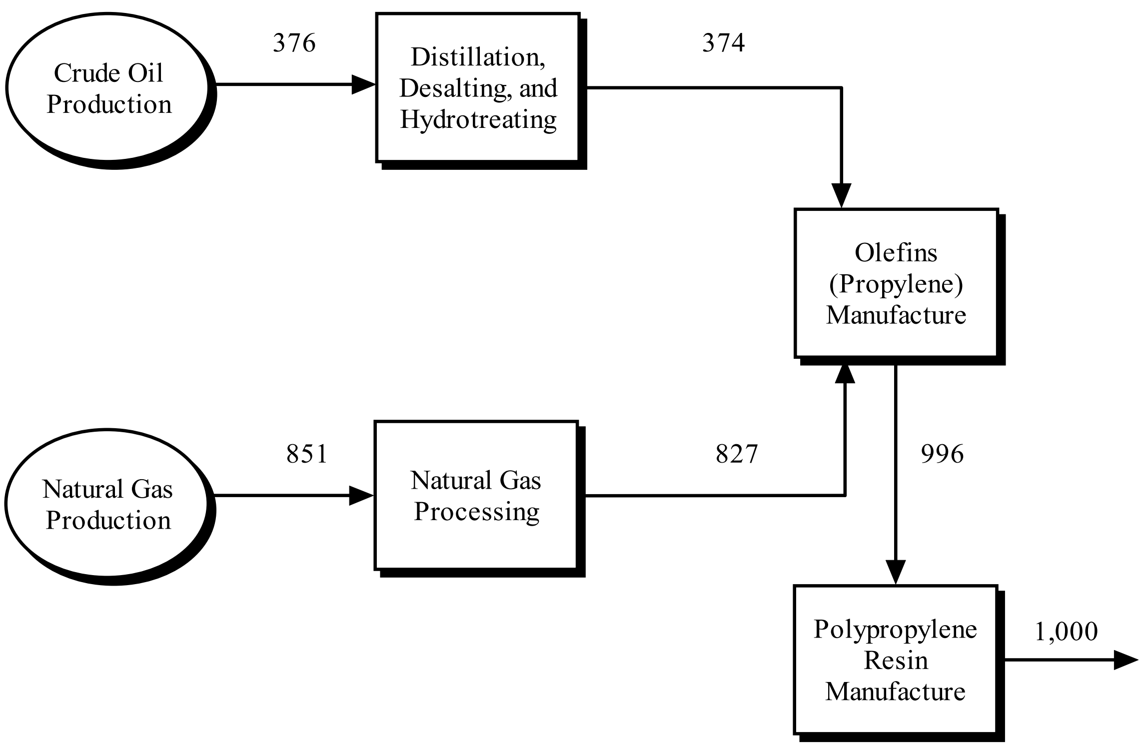


Figure C-4: Flow diagram for polypropylene production

Olefins Production (Propylene)

The primary process used for manufacturing olefins is the thermal cracking of saturated hydrocarbons such as ethane, propane, naphtha, and other gas oils.

Typical production of ethylene, propylene, and other coproducts begins when hydrocarbons and steam are fed to the cracking furnace. After being heated to temperatures around 1,000° Celsius, the cracked products are quenched in heat exchangers which produce high pressure steam. Fuel oil is separated from the main gas stream in a multi-stage centrifugal compressor. The main gas stream then undergoes hydrogen sulfide removal and drying. The final step involves fractional distillation of the various reaction products.

A weighted average using production amounts was calculated from the olefins production data collected from three leading producers (8 thermal cracking units) in North America. Transportation amounts for propylene were calculated using a weighted average of data collected from the polypropylene producers. Table C-8 shows the averaged energy and emissions data for the production of 1,000 pounds of propylene. Numerous coproduct streams are produced during this process. Fuel gas and off-gas were two of the coproducts produced; the energy amounts for these coproducts are reported separately as recovered energy. A mass basis was used to partition the credit the remaining products.

As of 2003, there were 8 olefin-producing companies and at least 16 olefin plants producing polymer-grade propylene in the U.S. (Reference C-151). While data was collected from a relatively small sample of plants, the olefins producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American olefins production. The average dataset was reviewed and accepted by all olefins data providers.

To assess the quality of the data collected for olefins, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for olefins include direct measurements, information provided by purchasing and utility records, and estimates. The standard production technology for olefins is the steam cracking of hydrocarbons (including natural gas liquids and petroleum liquids). The data in this module represent steam cracking of natural gas and petroleum. All data submitted for olefins represent the year 2003 and U.S. and Canada production.

Table C-8

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF PROPYLENE

				Total Energy Thousand Btu
Raw Materials (1)				
Refined petroleum products	311	lb		
Processed natural gas	716	lb		
Additional Raw Materials used for Internal Energy (2)				
Refined petroleum products	49.2	lb		
Processed natural gas	115	lb		
Water Consumption	211	gal		
Energy Usage				
Process Energy				
Electricity (grid)	46.0	kwh		489
Electricity (cogeneration)	21.4	kwh		146
Natural gas	1,697	cu ft		1,901
Gasoline	0.0021	gal		0.30
Diesel	0.0018	gal		0.29
Recovered Energy	3,172	thousand Btu		(3,172)
Total Process (Net)				(635)
Transportation Energy				
Propylene products				
Pipeline-petroleum products	19.5	ton-miles		
Electricity	0.43	kwh		4.35
Environmental Emissions				
Atmospheric Emissions				
Aldehydes	1.0E-07	lb	(3)	
Carbon Monoxide	0.084	lb		
Carbon Dioxide	1.00	lb	(3)	
Chlorine	1.0E-04	lb	(3)	
HCFC-022	1.0E-06	lb	(3)	
Hydrogen Chloride	1.0E-06	lb	(3)	
Hydrogen	0.0016	lb		
Hydrocarbons (NM)	0.049	lb		
Methane	0.022	lb		
Nitrogen Oxides	0.10	lb	(3)	
Nitrous Oxide	0.0010	lb	(3)	
Other Organics	0.0010	lb	(3)	
Particulates (unspecified)	0.014	lb		
Particulates (PM2.5)	1.0E-04	lb	(3)	
Particulates (PM10)	0.011	lb		
Sulfur Oxides	0.033	lb		
VOC	0.010	lb	(3)	
Solid Wastes				
Landfilled	0.36	lb		
Burned	5.56	lb		
Waste-to-Energy	0.0044	lb		
Waterborne Wastes				
Acetone	1.0E-09	lb	(3)	
Benzene	1.0E-05	lb	(3)	
BOD	5.8E-04	lb		
COD	0.010	lb	(3)	
Ethylbenzene	1.0E-06	lb	(3)	
Naphthalene	1.0E-09	lb	(3)	
Phenol	1.0E-04	lb	(3)	
Styrene	1.0E-07	lb	(3)	
Suspended Solids	0.0039	lb		
Toluene	1.0E-04	lb	(3)	
Total Organic Carbon	1.0E-04	lb	(3)	
Xylene	1.0E-07	lb	(3)	

(1) Specific raw materials from oil refining and natural gas processing include ethane, propane, liquid feed, heavy raffinate, and DNG.

(2) A portion of the material feed combusts within the hydrocracker, which provides an internal energy source.

(3) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

References: C-140 and C-144.

Source: Franklin Associates, A Division of ERG

Polypropylene Resin Production

Polypropylene is manufactured by the polymerization of propylene using Ziegler-Natta catalysts. Commercial processes generally use titanium trichloride in combination with aluminum diethylmonochloride. Production processes vary and include slurry, gas-phase, and solution monomer polymerization. The latter two processes employ the use of improved high-yield catalysts. The five polypropylene datasets represent the gas-phase and solution monomer polymerization processes. These processes are discussed below.

The gas-phase method of production mixes the high-yield type catalyst and propylene vapor in a fluidized bed or agitated powder bed reactor. Temperature control is accomplished by the evaporation of liquid propylene entering the reactor. Reactor temperatures of 80° to 90° Celsius and pressures of 30 to 35 atmospheres are typical. Unreacted propylene gas is recovered, compressed, purified, and returned to the propylene feed stream. The polymer is then dried and pelletized. Catalyst residues are low and catalyst removal is not part of this process. No solvent is used in the process; therefore, no solvent recovery is necessary.

The solution monomer process of manufacturing polypropylene often employs tubular reactors with a large specific-exchange surface and a high heat-exchange coefficient. The use of high-yield catalyst eliminates the need for catalyst residue and atactic removal. Unreacted propylene is recovered, and the isotactic polypropylene is dried and pelletized. As in the gas-phase process, no solvent is used.

A weighted average using production amounts was calculated from the PP production data from four plants collected from three leading producers in North America. Table C-9 displays the energy and emissions data for the production of 1,000 pounds of polypropylene resin. Scrap and some alkane/alkene streams are produced as coproducts during this process. A mass basis was used to partition the credit for the coproducts.

As of 2003 there were 11 PP producers and 20 PP plants in the U.S. (Reference C-154). While data was collected from a small sample of plants, the PP producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American PP production. The average dataset was reviewed and accepted by all PP data providers.

To assess the quality of the data collected for PP, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for PP include direct measurements, information provided by purchasing and utility records, and estimates. The technology represented by the PP data represents a combination of the liquid monomer and gas phase processes. All data submitted for PP represent the years 2003 and 2004 and production in U.S. For purposes of this analysis, the transportation distance from the resin manufacturer to a converter was estimated as 500 miles by truck.

Table C-9

**DATA FOR THE PRODUCTION OF
1,000 POUNDS OF POLYPROPYLENE (PP) RESIN**

				Total Energy Thousand Btu
Raw Materials				
Olefins	996	lb		
Propane	5.0	lb		
Water Consumption	139	gal		
Energy Usage				
Process Energy				
Electricity (grid)	74.0	kwh		762
Electricity (cogeneration)	68.4	kwh		467
Natural gas	310	cu ft		347
Residual oil	0.52	gal		89.2
Total Process				1,665
Transportation Energy				
Combination truck	250	ton-miles		
Diesel	3	gal		417
Environmental Emissions				
Atmospheric Emissions				
Carbon Monoxide	0.12	lb		
Carbon Dioxide	19.3	lb		
Lead	1.0E-12	lb	(1)	
Methane	0.068	lb		
Nitrogen Oxides	0.014	lb		
Nitrous Oxides	0.0045	lb		
NM Hydrocarbons	0.15	lb		
Other Organics	0.010	lb	(1)	
Particulates (unknown)	0.023	lb		
PM2.5	1.0E-05	lb	(1)	
PM10	0.0010	lb	(1)	
Sulfur Oxides	1.0E-04	lb	(1)	
Zinc	1.0E-06	lb	(1)	
Solid Wastes				
Landfilled	0.11	lb		
Burned	2.06	lb		
Waterborne Wastes				
BOD	0.0010	lb	(1)	
COD	0.010	lb	(1)	
Dissolved solids	0.010	lb	(1)	
Suspended Solids	0.020	lb		
Zinc	1.0E-05	lb	(1)	

(1) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

References: C-144

Source: Franklin Associates, A Division of ERG

POLYETHYLENE TEREPHTHALATE (PET)

This section discusses the manufacture of polyethylene terephthalate (PET) resin. The leading use of PET resin is bottle production. Over 7 billion pounds of PET was produced in the U.S., Mexico, and Canada in 2003 (Reference C-107). The material flow for PET resin is shown in Figure C-5. The following processes are included in this appendix:

- Crude Oil Production
- Distillation, Desalting, and Hydrotreating
- Natural Gas Production
- Natural Gas Processing
- Ethylene Production
- Methanol Production
- Carbon Monoxide Production
- Acetic Acid Production
- Oxygen Production
- Ethylene Oxide Production
- Ethylene Glycol Production
- Mixed Xylenes
- Paraxylene Extraction
- Crude Terephthalic Acid (TPA) Production
- Purified TPA (PTA) Production
- Dimethyl Terephthalate (DMT) Production
- PET Melt Phase Polymerization
- PET Solid Phase Polymerization

Crude oil production, petroleum refining (distillation, desalting, and hydrotreating), natural gas production, natural gas processing, and ethylene production are discussed previously in this appendix and are not repeated in this section. Details on the other processes of PET production are provided below.

The material flows for PET production are shown in Figure C-5 below.

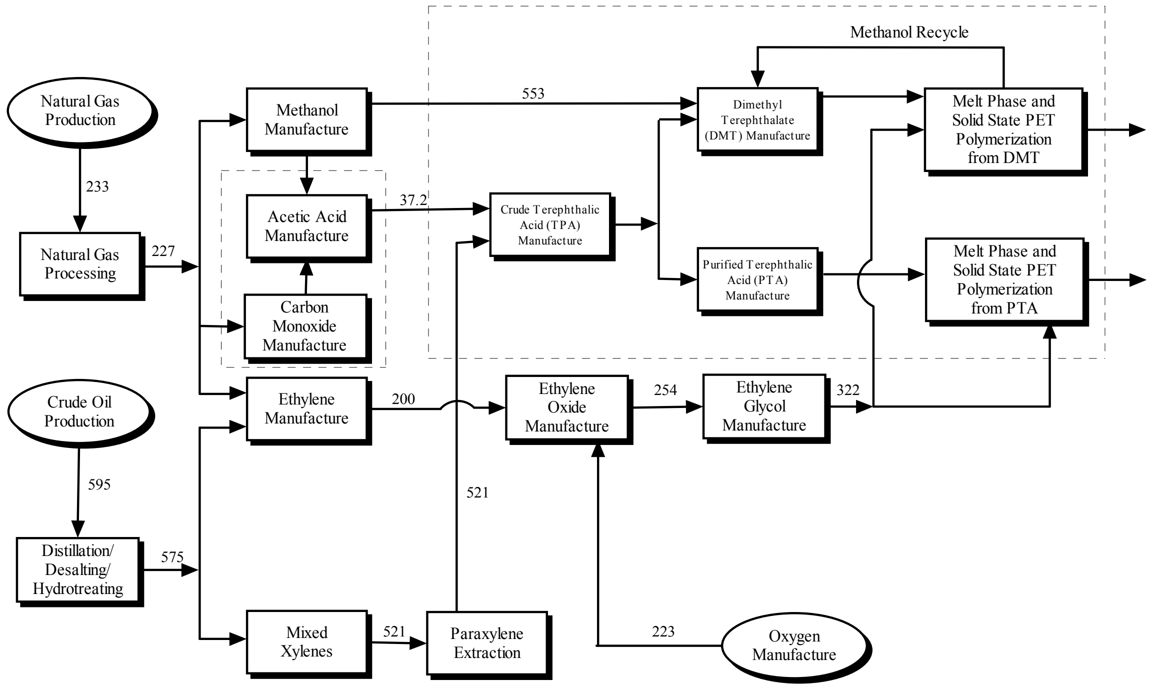


Figure C-5: Flow diagram for PET production

Methanol Production

Methanol is produced from light hydrocarbons using steam reforming and low-pressure synthesis. The feed gas is compressed, preheated, and desulfurized. Then, it is mixed with steam and fed to the catalytic reformer. The synthesis gas from the reformer, containing primarily hydrogen, carbon monoxide, and carbon dioxide, is cooled to remove condensate and reheated to the proper temperature for entry into the process-to-process interchanger.

From the interchanger, the feed goes to a multi-bed inter-cooled methanol converter system. Converter effluent is sent to a cooler, and the crude methanol is removed from the gas mixture. Distillation is used to eliminate dissolved gases from the methanol before refining the crude product to obtain the desired grade.

Table C-10 lists the energy requirements and environmental emissions for the manufacture of 1,000 pounds of methanol. The energy and emissions data for methanol are from secondary sources and estimates. The transportation energy was collected from an acetic acid producer and calculated using estimates.

Table C-10

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF METHANOL

			Total Energy Thousand Btu
Raw Materials			
Natural Gas	550	lb	
Energy Usage			
Process Energy			
Electricity (grid)	5.30	kwh	55
Natural gas	1,529	cu ft	1,712
Total Process			1,767
Transportation Energy			
Barge	25.0	ton-miles	
Diesel	0.020	gal	3.2
Residual oil	0.067	gal	11.4
Pipeline-natural gas	0.50	ton-miles	
Natural gas	0.35	cu ft	0.4
Total Transportation			15.0
Environmental Emissions			
Atmospheric Emissions			
Hydrocarbons	5.00	lb	
Solid Wastes			
Landfilled	0.50	lb	
Waterborne Wastes			
BOD	0.058	lb	
Suspended solids	0.088	lb	

References: C-46, C-146, C-158, C-159, and C-160.

Source: Franklin Associates, A Division of ERG

Carbon Monoxide Production

The raw materials necessary for the production of carbon monoxide are the gases resulting from steam reformation, as in the production of synthesis gas for ammonia manufacture, or from partial combustion of hydrocarbons. The feed gas must be stripped of carbon dioxide by scrubbing with ethanolamine solution and then passed through a molecular sieve to remove traces of carbon dioxide and water. Carbon monoxide and unconverted methane are condensed from the gas mixture and separated by lowering the pressure to remove entrained gases. The methane is recycled and the carbon monoxide comes out as a product after evaporation, warming, and compression.

The energy requirements and environmental emissions for the production of carbon monoxide using steam reformation are included in the production of acetic acid (Table C-11). The energy and emissions data for carbon monoxide are from secondary sources and estimates. The transportation energy was collected from an acetic acid producer and calculated using estimates.

Acetic Acid Production

Several methods are used for producing acetic acid. Some methods used in the United States include liquid phase oxidation of butane or LPG and the oxidation of acetaldehyde. Most commercial production of virgin synthetic acetic acid is made by reacting carbon monoxide with methanol. Recovered acetic acid represents an additional major supply (Reference C-146).

Table C-11 shows the energy and emissions data for producing acetic acid. Mixed acid and off-gas are produced as coproducts during this process. A mass basis was used to partition the credit for the acid, while the energy amount for the off-gas was reported separately as recovered energy.

The data in Table C-11 represents the production of acetic acid by the carbonylation of methanol. As only 2 confidential datasets were available, the carbon monoxide dataset is included within the acetic acid data. One of these datasets was collected for this project and represents 2003 data in the U.S., while the other U.S. dataset comes from 1994. As no production amounts were available for either datasets, an arithmetic average was used to weight the data. The 2003 data were collected from direct measurements and engineering estimates.

Table C-11

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF ACETIC ACID
(Includes data for the production of carbon monoxide and acetic acid)

Raw Materials			
Methanol	539	lb	
Natural Gas products	325	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	65.7	kwh	676
Electricity (cogeneration)	0.93	kwh	6.35
Natural gas	3,581	cu ft	4,011
Recovered energy	81.0	thousand Btu	81
Total Process			4,612
Transportation Energy			
Rail	475	ton-miles	
Diesel	1.18	gal	187
Pipeline-natural gas	0.26	ton-miles	
Natural gas	0.18	cu ft	0.20
Total Transportation			187.3
Environmental Emissions			
Atmospheric Emissions			
Carbon Monoxide	3.97	lb	
Carbon Dioxide	1.76	lb	
TOC	2.17	lb	
Methanol	0.040	lb	
Ammonia	0.57	lb	
Solid Wastes			
Landfilled	0.56	lb	
Waterborne Wastes			
Acid (unspecified)	0.96	lb	
Ammonia	0.052	lb	

References: C-160, C-161.

Source: Franklin Associates, A Division of ERG

Oxygen Production

Oxygen is manufactured by cryogenic separation of air. This technique is essentially one of liquefying air, then collecting the oxygen by fractionation. The oxygen is produced in the form of a liquid, which boils at 184° Celsius below zero at normal atmospheric pressure, so it must be kept under stringent conditions of temperature and pressure for handling. Most oxygen plants are located quite close to their point of consumption and use pipelines to minimize transportation difficulties, although there is a small amount of long distance hauling in insulated rail cars.

The energy data for producing oxygen is displayed in Table C-12. This energy data is primary data collected from 3 producers representing air separation for the years 1990 through 1993.

Table C-12

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF OXYGEN

Energy Usage		**Total Energy Thousand Btu**
Process Energy		
Electricity	62.2 kwh	662
Total Process		662

References: C-47

Source: Franklin Associates, A Division of ERG

Ethylene Oxide Production

The primary production method for ethylene oxide is the direct oxidation of ethylene using air or oxygen. The predominant feed for commercial oxidation processes is oxygen rather than air. The reaction is catalyzed by silver and is exothermic. Oil or boiling water is used to absorb the heat in a multitubular reactor and produce steam that is used in other parts of the process.

A disadvantage to the oxidation process is the conversion of ethylene to carbon dioxide and water, which is released to the environment. Excess ethylene is added to prevent additional oxidation of the ethylene oxide that would increase the production of carbon dioxide. This creates typical conversion rates for ethylene to ethylene oxide of only 10 to 20 percent per pass. Approximately 20 to 25 percent of the ethylene is broken down to carbon dioxide and water.

The energy requirements and environmental emissions for the production of 1,000 pounds of ethylene oxide are shown in Table C-13. These data are a straight average of 6 ethylene oxide producers in the U.S. and Europe from 1990 through 1992. This average data was sent to a Plastics Division of the American Chemistry Council (ACC) member company that produces ethylene oxide for review. The company agreed that the energy and emissions are acceptable for 2005; however, new raw material estimates were provided by the Plastics Division of the American Chemistry Council (ACC) member company.

Ethylene Glycol Production

Ethylene glycol is produced by the hydration of ethylene oxide. The production process is generally close to the process unit for ethylene oxide. Ethylene oxide is very hazardous to handle and transport. In this case, crude oxide solution is used as feed to the glycol unit. Using crude solution avoids a refining step but still provides an adequate feed.

An excess amount of water is added to the reactor feed to reduce the amount of diethylene glycol and triethylene glycol. These glycols are produced from the reaction of monoethylene glycol with ethylene oxide. The hydration reaction can be uncatalyzed or catalyzed with an acid. An uncatalyzed reaction is much slower, but acid removal from the glycol is required if a catalyst is used.

Almost all the ethylene oxide is reacted. This glycol/water mixture is sent through an evaporator to concentrate the solution and recover the water. The water is recycled back to be used to prepare the ethylene oxide feed. High purity ethylene glycol is obtained from the concentrated glycol solution by vacuum distillation.

Table C-13

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF ETHYLENE OXIDE

			Total Energy Thousand Btu
Raw Materials			
Ethylene	788	lb	
Oxygen	880	lb	
Energy Usage			
Process Energy			
Electricity (grid)	101	kwh	1,041
Natural gas	1,618	cu ft	1,812
Total Process			2,854
Transportation Energy			
Used in PET			
Pipeline-petroleum produ	1.00	ton-miles	
Electricity	0.022	kwh	0.22
Total Transportation			0.22
Used in polyether polyol for flexible foam PUR			
Rail	12.4	ton-miles	
Diesel	0.031	gal	4.88
Pipeline-petroleum produ	0.31	ton-miles	
Electricity	0.0068	kwh	0.069
Total Transportation			4.95
Environmental Emissions			
Atmospheric Emissions			
Aldehydes	0.28	lb	
Carbon Monoxide	3.0E-04	lb	
Carbon Dioxide	591	lb	
Ethylene Oxides	0.095	lb	
Hydrocarbons	18.1	lb	
Methane	3.05	lb	
Nitrogen Oxides	0.0014	lb	
Other Organics	0.68	lb	
Sulfur Oxides	3.0E-04	lb	
Solid Wastes	16.8	lb	
Waterborne Wastes			
Aldehydes	0.10	lb	
Ammonia	5.0E-05	lb	
BOD	2.23	lb	
Chromium	0.025	lb	
COD	2.82	lb	
Fluorides	2.0E-04	lb	
Zinc	0.010	lb	

References: C-146, C-158, C-163, C-164.

Source: Franklin Associates, A Division of ERG

The energy and emissions data for ethylene glycol production is from a confidential source and is not shown in this appendix (Reference C-167).

Mixed Xylenes

The reforming processes are used to convert paraffinic hydrocarbon streams into aromatic compounds such as benzene, toluene, and xylene. Catalytic reforming has virtually replaced thermal reforming operations. Catalytic reforming has many advantages over thermal reforming including the following:

1. Greater production of aromatics
2. More olefin isomerization
3. More selective reforming and fewer end products
4. Operated at a low pressure, hence comparatively lower cost.

Catalysts such as platinum, alumina, or silica-alumina and chromium on alumina are used.

Table C-14 displays the energy and emissions data for the production of 1,000 pounds of mixed xylenes. Total energy data for mixed xylenes were provided for this analysis by a confidential source. The mix of fuels shown in Table C-14 was calculated using statistics from a U.S. Department of Energy report (Reference C-67). No environmental emissions data were available.

Table C-14

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF MIXED XYLENES FROM NAPHTHA

Raw Materials			
Naphtha	1,000	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	16.1	kwh	166
Natural gas	667	cu ft	747
LPG	0.25	gal	27.0
Coal	7.02	lb	78.8
Total Process			1,019

References: C-158, C-165, and C-67.

Source: Franklin Associates, A Division of ERG

Paraxylene Extraction

Reformate feedstock rich in xylenes is fractionated to obtain a stream rich in the para-isomer. Further purification is accomplished by heat exchange and refrigeration. The solid paraxylene crystals are separated from the feedstock by centrifugation.

Table C-15 displays the energy requirements for the production of 1,000 pounds of paraxylene. Total energy data for paraxylene were provided for this analysis by a confidential source. The mix of fuels shown in Table C-15 was calculated using statistics from a U.S. Department of Energy report (Reference C-67). No environmental emissions data were available.

Table C-15

DATA FOR THE EXTRACTION OF 1,000 POUNDS OF PARAXYLENE

Raw Materials			
Mixed Xylenes	1,000	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	59.0	kwh	607
Natural gas	2,445	cu ft	2,738
LPG	0.91	gal	98.4
Coal	25.7	lb	289
Total Process			3,733
Transportation Energy			
Rail	650	ton-miles	
Diesel	1.61	gal	256
Total Transportation			256

References: B-40, B-42, B-50, and B-51.

Source: Franklin Associates, A Division of ERG

Crude Terephthalic Acid (TPA) Production

Crude terephthalic acid is manufactured primarily by the oxidation of paraxylene in the liquid phase. Liquid paraxylene, acetic acid, and a catalyst, such as manganese or cobalt bromides, are combined as the liquid feed to the oxidizers. The temperature of this exothermic reaction is maintained at about 200° C. The pressure may range from 300 to 400 psi.

Reactor effluents are continuously removed from the reactor and routed to a series of crystallizers, where they are cooled by flashing the liquids. The partially oxidized impurities are more soluble in acetic acid and tend to remain in solution, while crude TPA crystallizes from the liquor.

The slurry from the crystallizers is sent to solid/liquid separators, where crude TPA is recovered in the solids. The liquid portion is distilled and acetic acid, methyl acetate, and water are recovered overhead. Acetic acid is removed from the solution and recycled back to the oxidizer.

Purified Terephthalic Acid (PTA) Production

There are two primary methods of crude TPA purification. The first, described here, is by direct production of fiber-grade TPA or purified terephthalic acid (PTA).

In the production of fiber-grade TPA from crude TPA, the crude acid is dissolved under pressure in water at 225 to 275° C. The solution is hydrogenated in the presence of a catalyst to convert some troublesome intermediates of reaction. The solution is then cooled, causing PTA to crystallize out.

Dimethyl Terephthalate (DMT) Production

The other primary method of crude TPA purification is by conversion of crude TPA to dimethyl terephthalate (DMT). DMT now makes up no more than 15 percent of the precursors used for PET production within North America.

The common method for the production of DMT consists of four major steps: oxidation, esterification, distillation, and crystallization. A mixture of p-xylene and crude PTA is oxidized with air in the presence of a heavy metal catalyst. The acid mixture resulting from the oxidation is esterified with methanol to produce a mixture of esters. The crude ester mixture is distilled to remove all the heavy boilers and residue produced; the lighter esters are recycled to the oxidation section. The raw DMT is then sent to the crystallization section for removal of DMT isomers and aromatic aldehydes. Some byproducts are recovered, and usable materials are recycled (Reference C-171).

PET Melt Phase Polymerization

PET resin is manufactured by the esterification of PTA with ethylene glycol and loss of water, or by the trans-esterification of DMT with ethylene glycol and loss of methanol. Both reactions occur at 100 to 150° C in the presence of a catalyst. Bis (2-hydroxyethyl) terephthalate is produced as an intermediate. This intermediate then undergoes polycondensation under vacuum at 10 to 20° C above the melting point of PET (246° C). Ethylene glycol is distilled over, and PET resin with an I.V. (intrinsic viscosity) of 0.60 to 0.65 is produced. The resulting resin is cooled and pelletized.

PET Solid State Polymerization

The final step in PET resin manufacture is a solid state polymerization process. This step raises the temperature of the solid pellets to just below the melting point in the presence of a driving force to further the polymerization. Solid stating increases the final I.V. from 0.72 to 1.04. It also produces a polymer with low acetaldehyde content.

Table C-16 shows the combined energy usage and environmental emissions for the melt phase and the solid state polymerization steps for production of 1,000 pounds of PET from both PTA and DMT. Scrap and heat are produced as coproducts during this process. A mass basis was used to partition the credit for scrap. The energy shown in the table has been adjusted to subtract the energy reported by producers as being exported from the system as steam.

The data in this table includes an aggregation of TPA, PTA, DMT, and PET production. New data was collected for PTA (including TPA) and PET production. A weighted average using production amounts was calculated from the PTA production data from two plants collected from two leading producers in North America. A weighted average using production amounts was also calculated from the PET production data from two plants collected from two leading producers in North America. Data from primary sources in the early 1990's was used for DMT and PET from DMT production. The two PET technologies were weighted accordingly at 15 percent PET from DMT and 85 percent PET from PTA.

As of 2003 there were 16 PET producers and 29 PET plants in the U.S. (Reference C-146). As of 2001 there were 4 TPA/PTA producers and 6 TPA/PTA plants in the U.S. (Reference C-146). While data was collected from a small sample of plants, the PTA and PET producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American TPA/PTA and PET production. The average TPA/PTA and PET datasets were reviewed and accepted respectively by each TPA/PTA and PET data provider.

To assess the quality of the data collected for TPA/PTA, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for TPA/PTA include direct measurements, information provided by purchasing and utility records, and estimates. All data submitted for TPA/PTA represent the years 2001, 2003, and 2004 and production in the U.S.

To assess the quality of the data collected for PET from PTA, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for PET include direct measurements, information provided by purchasing and utility records, and estimates. The technology represented by the PET data is the esterification of PTA with ethylene glycol. All data submitted for PET represent the years 2001, 2003, and 2004 and production in the U.S. For purposes of this analysis, the transportation distance from the resin manufacturer to a converter was estimated as 500 miles by truck.

Table C-16

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF PET RESIN (1) (Includes PET resin, PTA, DMT, and TPA)

			Total Energy Thousand Btu
Raw Materials (2)			
Paraxylene	521	lb	
Ethylene glycol	322	lb	
Acetic acid	37.2	lb	
Methanol	35.2	lb	
Water Consumption	64.4	gal	
Energy Usage			
Process Energy			
Electricity (grid)	253	kwh	2,691
Electricity (cogeneration)	23.2	kwh	158
Natural gas	1,530	cu ft	1,714
Bituminous/Subbituminous Coal	18.4	lb	207
Distillate oil	1.40	gal	222
Residual oil	3.21	gal	551
Total Process			5,543
Transportation Energy			
Combination truck	250	ton-miles	
Diesel	3	gal	417
Environmental Emissions			
Atmospheric Emissions			
Acetic Acid	0.051	lb	
Aldehydes	0.094	lb	
Bromine	0.079	lb	
Carbon Dioxide	72.4	lb	
Carbon Monoxide	5.68	lb	
Methane	0.16	lb	
Methyl Acetate	0.040	lb	
NM Hydrocarbons	0.28	lb	
Nitrogen Oxides	0.052	lb	
Other Organics	0.94	lb	
Particulates (unknown)	0.15	lb	
Xylene	0.041	lb	
Solid Wastes			
Landfilled	4.19	lb	
Burned	0.31	lb	
Waste-to-Energy	0.59	lb	
Waterborne Wastes			
Aluminum	9.7E-07	lb	
Ammonia	0.11	lb	
Ammonium ion	0.0013	lb	
Antimony	9.7E-07	lb	
BOD	0.30	lb	
COD	0.76	lb	
Dissolved solids	0.030	lb	
Iron	9.7E-07	lb	
Metal ion	4.5E-06	lb	
Phenol	3.6E-06	lb	
Phosphates	5.1E-04	lb	
Suspended solids	0.054	lb	
TOC	0.044	lb	
Zinc	0.0055	lb	

(1) PET dataset represents 15 percent from DMT technology and 85 percent from PTA technology.

(2) Methanol is produced as a coproduct of PET production from DMT. This coproduct is sent to the DMT production facilities. Due to the boundaries for this table, the recycled methanol amount is not included in the methanol raw materials.

References: C-67, C-162 through C-166, C-168, and C-169.

Source: Franklin Associates, A Division of ERG

POLYCARBONATE

Polycarbonate is a transparent, thermoplastic polymer that has high impact strength (References C-52 and C-155). Polycarbonate is produced by the reaction of phosgene with bisphenol-A (References C-52 and C-155). The raw materials for phosgene production include chlorine and carbon monoxide; chlorine is produced by the electrolysis of salt and carbon monoxide can be produced from the partial combustion of carbon-containing materials (such as coal or natural gas) (Reference C-155). The raw materials for bisphenol-A production include phenol and acetone, which are produced by a series of petroleum and refining processes (Reference C-155).

No LCI data are available for polycarbonate production in the United States. This analysis uses polycarbonate data developed by Plastics Europe (Reference C-155). A limitation of the Plastics Europe data for polycarbonate production is that it aggregates all processes from cradle to resin; however, Plastics Europe data does provide sufficient data so that cradle-to-resin raw materials, primary fuels, electricity, and process emissions can be determined. Data for the cradle-to-resin production of polycarbonate are shown in Table C-17. The data in Table C-17 is based on the production technologies and raw materials for polycarbonate (and upstream materials) in Europe; however, it is assumed that these activities are similar between Europe and the United States (Reference C-156). To adapt the data in Table C-17 to U.S. operations, the inputs of primary fuels and electricity will be modeled using the energy and emissions for fuel production and combustion in the United States.

Table C-17

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF POLYCARBONATE

Energy Usage			**Total Energy Thousand Btu**
Energy of Material Resource			
Natural Gas	449	lb	10,450
Petroleum	273	lb	5,328
Coal	0.33	lb	4.30
Total Resource			15,782
Process Energy			
Electricity (grid)	556	kwh	5,918
Natural gas	17,604	cu ft	19,716
Coal	346	lb	3,887
Distillate oil	29.7	gal	4,713
Total Process			34,233
Transportation Energy			
Rail	332	ton-miles	
Diesel	0.82	gal	131
Ocean freighter	883	ton-miles	
Diesel	0.17	gal	26.6
Residual	1.51	gal	259
Pipeline-natural gas	416	ton-miles	
Natural gas	287	cu ft	321
Total Transportation			738
Environmental Emissions			
Atmospheric Emissions			
Particulates (PM10)	0.19	lb	
Carbon monoxide	4.10	lb	
Carbon dioxide (fossil)	250	lb	
Sulfur dioxide	0.33	lb	
Nitrogen dioxide (NO2)	0.57	lb	
Chlorine	0.0020	lb	
Hydrogen chloride	0.021	lb	
Non-methane hydrocarbons	2.00	lb	
Aldehydes (unspecified)	0.064	lb	
Organics (unspecified)	0.41	lb	
Hydrogen	0.66	lb	
CFC/HCFC/HFC (unspecified)	0.0010	lb	
Organo-chlorine (unspecified)	0.42	lb	
Methane	1.40	lb	
Aromatic hydrocarbons	0.097	lb	
NMVOC	0.0090	lb	
Ethylene	0.0020	lb	
Benzene	0.0050	lb	
Toluene	0.0010	lb	
Propylene	0.0010	lb	
Solid Wastes			
Landfilled	26.9	lb	
Waterborne Wastes			
COD	1.20	lb	
BOD	0.13	lb	
Iron	0.063	lb	
Sodium	430	lb	
Acid as H+	0.0020	lb	
Nitrate	0.0020	lb	
Metals (unspecified)	0.35	lb	
Ammonium	0.0010	lb	
Chloride	570	lb	
Organics (unspecified)	0.57	lb	
Suspended solids	0.98	lb	
Detergents and oil	0.0090	lb	
Hydrocarbons (unspecified)	0.0010	lb	
Organo chlorine (unspecified)	0.0040	lb	
Phenols	0.094	lb	
Dissolved solides (unspecified)	0.40	lb	
Phosphorus	0.23	lb	
Nitrogen	0.0060	lb	
Sulfate	13.0	lb	
Calcium	0.43	lb	
Magnesium	0.0040	lb	
Chlorate	0.0060	lb	
TOC	0.26	lb	
Haloalkanes (AOX)	0.0020	lb	
Carbonate	45.0	lb	

Source: Franklin Associates, A Division of ERG

POLYESTER COPOLYMER

Rigid clear plastic personal drinking water containers (such as Nalgene sport bottles) have traditionally been made from polycarbonate. However, due to recent questions about the potential health effects of bisphenol-A, a chemical used in the production of polycarbonate, new materials are increasingly being used as substitutes for polycarbonate in the manufacture of personal water bottles. The Nalgene website shows that Eastman Tritan™, a polyester copolymer, is being used in their bottles. However, no data on the production of this copolymer is available. Therefore, reusable plastic drinking containers are modeled in this analysis as PET, which has been described previously in this appendix.

POLYLACTIDE (PLA) POLYMER

While conventional plastics are produced using petroleum and natural gas as feedstock materials, PLA resin is produced from corn. Currently, NatureWorks® is the dominant North American producer of PLA. NatureWorks has published life cycle data on PLA production (Reference C-174); however, the aggregated data published by NatureWorks encompass all steps from corn growing through PLA resin pellets. The aggregated NatureWorks PLA data sets were developed using unit process data from other NatureWorks life cycle studies (e.g., on corn production and dextrose production) that are not publicly accessible, and the published aggregated data are shown on the basis of MJ of energy rather than units of specific fuels and electricity. In order to model the associated fuel combustion emissions and precombustion energy and emissions consistently with other materials in this study, more detail on specific fuels and electricity use is needed. Therefore, in this analysis, PLA production is based on Franklin Associates' U.S. corn production data, which are derived from published USDA data (Reference C-173), and process data for the conversion of corn into PLA resin from the Ecoinvent database (Reference C-170). The Ecoinvent data set for conversion of corn into PLA is based on NatureWorks 2005 PLA production and reports process energy by specific fuel types and kWh of electricity. The following sections describe the corn growing and PLA production processes.

The corn growing data for corn used as an input to PLA production were based on a 2002 USDA Agricultural Economic Report (Reference C-173) and are shown in a later section of this appendix as Table C-51. The data are from the Agricultural Resource Management Survey (ARMS) and represent a weighted average of the nine major corn-producing states that account for about 80 percent of U.S. corn production. Inputs of fertilizer and fuels for corn acreage planted in each state were aggregated based on each state's corn production to estimate an average input level for corn production.

While this provides a good U.S. average for corn production, it should be noted that there were large variations among individual states' average data for corn yield per acre and use of fertilizers and energy per acre. There are also significant year-to-year variations in yields per acre, depending on, among other things, annual weather conditions in each state. Thus, the uncertainty in the corn-growing data is larger than the uncertainty for other industrial processes in the Franklin database. The scope of this analysis did not include evaluation of the full range of corn growing fertilizer inputs, energy inputs, and corn yields per acre.

When corn grain is produced, corn stover (stalks and leaves) is coproduced. There are several ways in which corn stover can be managed. It may be left in the field to decompose, used for animal feed, or burned. In addition, there have been some efforts to utilize corn stover as a source of biomass-derived energy. The study used as the source of the corn growing data did not explicitly discuss the quantity of stover and whether it was treated as a co-product or as a waste; the implicit assumption is that the stover was neither allocated any co-product benefits nor assigned any waste management burdens, which would correspond with a scenario in which the stover is simply left in the field to decompose. Thus, in this analysis, all of the corn growing burdens are allocated to the corn.

Biomass such as corn plants remove carbon dioxide from the air during growth. In this study, carbon sequestration credit is given only for the carbon content of PLA that ends up in a landfill. Based on information on NatureWorks' website, PLA could decompose under certain landfill conditions. NatureWorks LLC's website states that PLA in an inactive landfill (i.e., low temperature, limited moisture) would not become biologically active, although PLA placed in a biologically active landfill would actively biodegrade, contributing to methane production.[3] Temperature and moisture conditions in Oregon landfills may be sufficient to support hydrolysis. Because of the uncertainty surrounding PLA degradation in landfills, the LCI model was set up to evaluate a range of decomposition scenarios for landfilled PLA containers. The ultimate fate of the carbon in other parts of the corn plant such as the stover is unknown and is likely to eventually return to the atmosphere as carbon dioxide, e.g., via decomposition in the field or combustion.

For this analysis, it is assumed that the land used to grow the corn was already in use for agricultural purposes and did not require converting land from its natural state. Recent studies have indicated that carbon sequestration effects associated with changes in landcover can be significant; however, modeling of land use conversion was beyond the scope of this study.

Corn grain is transported to a wet mill where the starch is separated and hydrolyzed to dextrose. The dextrose solution is piped to the adjacent PLA plant, where fermentation produces lactic acid. The lactic acid is converted into lactide, which is purified and then polymerized.

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[3] NatureWorks LLC Landfill website: http://www.natureworksllc.com/our-values-and-views/end-of-life/landfill.aspx

The energy results obtained by using the U.S. corn growing data and the Ecoinvent PLA data in the Franklin LCI model were checked against published energy results for NatureWorks PLA (Reference C-174). Cradle-to-resin energy for PLA as modeled by Franklin (using U.S. corn growing data and the Ecoinvent data set for production of PLA from corn) is approximately 30 million Btu per 1000 lb, compared to 32.4 million Btu per 1000 lb (75.4 MJ/kg) reported for NatureWorks PLA production using grid electricity (PLA5). This energy comparison of the PLA and Franklin model results includes the energy content of the corn used as a material input, which is the convention used by NatureWorks. Without access to the unpublished unit process data on corn production and PLA production steps used in the NatureWorks life cycle studies, it is not possible to further resolve the differences in total energy.

In 2006, NatureWorks began purchasing wind energy credits to offset fossil energy use and carbon dioxide emissions associated with the production of PLA, and in 2009 NatureWorks indicated that they have stopped purchasing wind energy credits due to process improvements that have significantly reduced their energy and carbon dioxide emissions for PLA production.[4] Although NatureWorks has published bottom-line cradle-to-resin results for MJ of energy and kg of carbon dioxide equivalents released per kg of PLA for the improved process, process data are not available at a level of detail to support LCA modeling for this report. Therefore, the results in this analysis are based on 2005 process data.

Aggregated cradle-to-resin results for NatureWorks 2005 PLA production are shown in Table C-18. Material inputs and associated energy content are not shown in these tables to prevent the possibility of backing out results for the Ecoinvent corn-to-PLA data set, which is available only to licensed users of Ecoinvent. Although the total cradle-to-resin energy requirements for PLA production are approximately 30 million Btu when the energy content of the corn feedstock is included, it is important to note that Franklin Associates' LCI methodology does not assign energy of material resource to corn, so the results shown for PLA bottles in the Oregon bottled water report are based on the process and transportation energy shown in Table C-18.

4 http://www.natureworksllc.com/news-and-events/press-releases/2009/02-10-09-ingeo-ecoprofile.aspx

Table C-18

DATA FOR THE PRODUCTION OF
1,000 POUNDS OF POLYLACTIDE RESIN (PLA5)
(aggregated cradle-to-PLA using grid electricity)

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	862	kwh	9,175
Natural gas	7,987	cu ft	8,945
LPG	1.37	gal	148
Coal	2.12	lb	23.8
Distillate oil	0.50	gal	79.3
Residual oil	0.072	gal	12.3
Gasoline	0.66	gal	94.5
Diesel	1.85	gal	294
Total Process			18,772
Transportation Energy			
Combination truck	122	ton-miles	
Diesel	1.28	gal	203
Rail	280	ton-miles	
Diesel	0.69	gal	110
Barge	265	ton-miles	
Diesel	0.21	gal	33.7
Residual oil	0.71	gal	121
Ocean freighter	11.9	ton-miles	
Diesel	0.0023	gal	0.36
Residual	0.020	gal	3.48
Pipeline-natural gas	4.76	ton-miles	
Natural gas	3.28	cu ft	3.68
Pipeline-petroleum products	2.21	ton-miles	
Electricity	0.048	kwh	0.49
Total Transportation			476

Environmental Emissions

Atmospheric Emissions		
Particulates (unspecified)	1.32	lb
Nitrogen Oxides	0.0053	lb
Non-Methane Hydrocarbons	2.72	lb
Sulfur Oxides	1.01	lb
Carbon Monoxide	0.10	lb
Aldehydes (unspecified)	0.0010	lb
Methane	0.15	lb
Other Organics	0.028	lb
Ammonia	0.028	lb
Carbon Dioxide - Fossil	5.57	lb
Carbon Dioxide - Non-Fossil	0.50	lb
Carbon Tetrachloride	9.4E-11	lb
CFCs	9.4E-10	lb
Trichloroethane	7.6E-10	lb
VOC	0.0073	lb
Solid Wastes		
Landfilled	3.55	lb
Burned	4.80	lb
Waste-to-Energy		lb
Waterborne Wastes		
Acid (unspecified)	0.0071	lb
Dissolved Solids	8.17	lb
Suspended Solids	0.37	lb
BOD	1.85	lb
COD	2.97	lb
Phenol/ Phenolic Compounds	3.6E-05	lb
Sulfides	1.5E-06	lb
Oil	0.0029	lb
Iron	0.0075	lb
Cyanide	6.4E-06	lb
Alkalinity	0.0056	lb
Chromium (unspecified)	9.4E-05	lb
Aluminum	0.0033	lb
Nickel	1.5E-05	lb
Mercury	3.6E-08	lb
Lead	3.0E-05	lb
Zinc	8.0E-05	lb
Ammonia	0.0027	lb
Sulfates	0.0052	

References: C-48,C-49,C-51,C-52, C-69,C-71 through C-87, C-170.

Source: Franklin Associates, A Division of ERG

GLASS

This section discusses the manufacture of container glass. The following processes are included in this appendix:

- Glass Sand Mining
- Limestone Mining
- Soda Ash Mining and Processing
- Feldspar Mining
- Cullet (In-House)
- Cullet (Postconsumer)
- Virgin Glass Production
- Recycled Glass Production

The material flows for glass production are shown in Figure C-6. Details on the unit process of glass production are provided below.

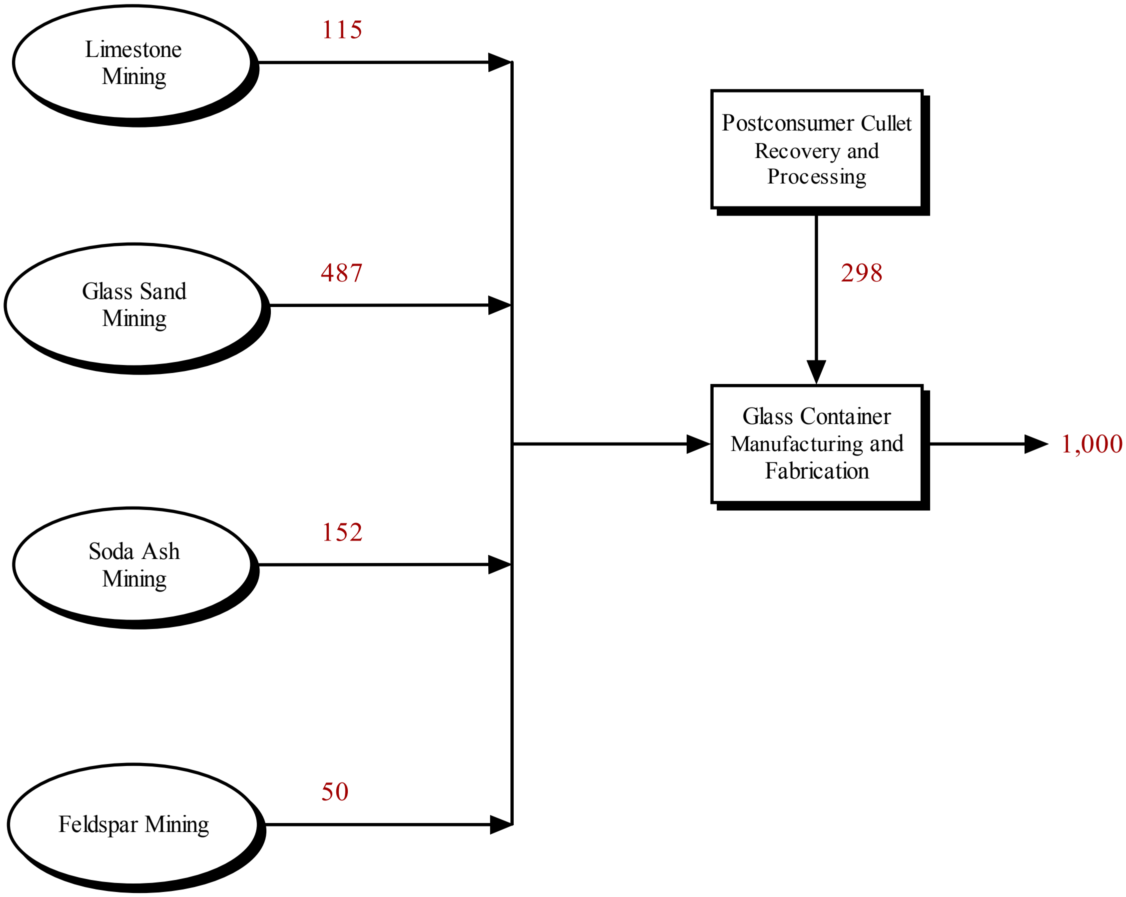

Figure C-6: Flow diagram for glass container production

Glass Sand Mining

Glass sand, the predominant raw material for glass manufacture, is the source of almost all of the silicon dioxide present in the finished glass. Silicon dioxide accounts for approximately 70 percent by weight of finished glass.

Glass sand is a high purity quartz sand with high silica content and typically less than one percent of iron oxide, chromium compounds, and alumina, calcium, or magnesium oxides. In general, the U.S. consumption of glass sand is met by U.S. production, but some high purity glass sand is imported. Glass sand deposits exist in New Jersey in the form of unconsolidated sand banks, and as sandstone found in the Allegheny and the Mississippi Valley. The east-west belt of states running from Pennsylvania to Illinois has rich resources for glass sand.

Mining operations vary depending on the nature of the deposit at each location. Open pit excavation and dredging are the two basic mining methods, each requiring a combination of many types of equipment including crushers, screens, washers, classifiers, and grinding mills. The LCI data used for this step are based on open pit (dry) excavation. The energy requirements and environmental emissions for the mining and processing of glass sand are shown in Table C-19. Particulates are generated especially during drying and packaging operations (Reference C-2). Waterborne suspended solids from clay are generated during washing operations (Reference C-3).

Table C-19

**DATA FOR THE MINING
OF 1,000 POUNDS OF GLASS SAND (SILICA)**

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	10.1	kwh	104
Natural gas	113	cu ft	127
Distillate oil	0.10	gal	15.9
Residual oil	0.030	gal	5.15
Gasoline	0.0077	gal	1.09
Total Process			253
Transportation Energy			
Combination truck	105	ton-miles	
Diesel	1.10	gal	175
Rail	5.60	ton-miles	
Diesel	0.014	gal	2.21
Total Transportation			177
Environmental Emissions			
Atmospheric Emissions			
Particulates	0.024	lb	
Nitrogen oxides	0.016	lb	
Carbon dioxide	14.0	lb	
Waterborne Wastes			
Suspended solids	1.00	lb	

References: C-2, C-7, C-8, and C-17.

Source: Franklin Associates, A Division of ERG

Limestone Mining

Limestone is quarried primarily from open pits. The most economical method of recovering the limestone has been through blasting, followed by mechanical crushing and screening.

Particulate emissions arise from limestone crushing and screening operations (Reference C-92). Based on the type of technologies employed for limestone mining and processing, it is assumed that the release of other air emissions or water effluents is negligible (References C-68 and C-69).

It is assumed that negligible solid wastes are produced from limestone mining and processing. Any overburden or tailings produced from limestone mining and processing are returned to the mine site (References C-68 and C-69).

Energy requirements for limestone mining shown in Table C-20 are based on recent U.S. commerce statistics presented in a U.S. Department of Energy environmental profile (Reference C-60).

Table C-20

DATA FOR THE MINING OF 1,000 POUNDS OF LIMESTONE

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	1.92	kwh	20.4
Natural Gas	2.25	cu ft	2.52
Coal	0.036	lb	0.40
Distillate Oil	0.070	gal	11.1
Gasoline	0.0061	gal	0.87
Total Process			35.3
Transportation Energy			
Combination Truck	21.0	ton-miles	
Diesel	0.22	gal	35.0
Rail	5.00	ton-miles	
Diesel	0.012	gal	1.97
Barge	13.0	ton-miles	
Diesel	0.010	gal	1.65
Residual Oil	0.035	gal	5.93
Total Transportation			44.6
Environmental Emissions			
Atmospheric Emissions			
Particulates (unspecified)	0.051	lb	

References: C-90 and C-91

Source: Franklin Associates, A Division of ERG

Soda Ash Mining and Processing

Soda ash used in the U.S. is naturally occurring and is obtained from trona and alkaline brines in the Green River basin in Wyoming and Searles Lake in California. The soda ash is mined using two different methods, underground trona mining and solution mining. Underground trona mining is similar to coal mining. The most common methods are the room and pillar method and the long wall method. In both of these processes, the material is undercut, drilled, blasted, crushed, and then transported to the surface.

Solution mining is currently being used by one of the six major soda ash producers in the U. S. The soda ash from solution mining is for the most part used for the manufacture of caustic soda. The data in this report are based on underground trona mining.

After mining, the trona is crushed, screened and then calcined in rotary gas-fired kilns. The mineral is next dissolved in water and then filtered. The resulting soda ash solution (sodium carbonate) is evaporated and then dried. Solid wastes are generated from impurities filtered out during refining. Airborne particulates from mining and drying operations are also generated.

Soda ash can also be produced synthetically via the Solvay process. The Solvay process uses salt, coke, and limestone, with ammonia as a catalyst. Synthetic soda ash is more expensive to produce than natural soda ash and also has high concentrations of calcium chloride and sodium chloride in the process effluent. This method of soda ash production is not currently being used in the U.S.

U.S. production provides nearly all of the soda ash required by U.S. manufacturers. Approximately 45 percent of the total soda ash manufactured is used in glass manufacturing. For the purposes of this analysis, only natural soda ash mined underground is assumed to be used in glass manufacturing. The energy and emissions for the mining and processing of soda ash are shown in Table C-21.

Table C-21

**DATA FOR THE MINING
OF 1,000 POUNDS OF SODA ASH**

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	41.1	kwh	423
Natural gas	797	cu ft	893
Coal	108	lb	1,208
Distillate oil	0.067	gal	10.7
Residual oil	0.19	gal	31.8
Total Process			2,567
Transportation Energy			
Rail	400	ton-miles	
Diesel	1	gal	158
Environmental Emissions			
Atmospheric Emissions			
Carbon dioxide, fossil*	415	lb	
Particulates (unspecified)	96.5	lb	

*Carbon dioxide releases associated with fossil mineral deposits, not fossil fuel combustion.

References: C-12, C-15, and C-18.

Source: Franklin Associates, A Division of ERG

Feldspar Mining

Feldspar is an aluminum silicate mineral that is used in glass manufacture to obtain aluminum oxide. This oxide improves the stability and durability of the glass microstructure.

Feldspar is mined in seven states, but North Carolina produces the majority of the nation's total. It is mined primarily by open pit quarry techniques. The data in this report for feldspar mining are based on open pit mining. The deposit material is removed from the quarry and crushed. The crushed material is then sent through flotation processes to remove minerals, to lower the iron content, and to purify the feldspar to glass-grade products. The feldspar is used in the manufacture of glass in the form of a silica mixture or as a quartz.

The energy and emissions for mining and processing of feldspar are shown in Table C-22. The majority of the non-feldspar material recovered with this mineral is sold as a coproduct. The remainder of the material is placed in settling ponds and used for land cover. Therefore, no solid waste is associated with the mining and processing of feldspar (References C-4 and C-5). The air pollution generated is primarily particulates produced during the mining and crude ore processing.

Table C-22

DATA FOR THE MINING OF 1,000 POUNDS OF FELDSPAR

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	6.60	kwh	67.9
Natural gas	122	cu ft	137
Distillate oil	0.16	gal	25.4
Residual oil	0.16	gal	27.5
Gasoline	0.010	gal	1.42
Total Process			259
Transportation Energy			
Rail	200	ton-miles	
Diesel	0.50	gal	78.8
Total Transportation			78.8
Environmental Emissions			
Atmospheric Emissions			
Particulates	0.60	lb	
Carbon dioxide, fossil*	51.0	lb	

*Carbon dioxide releases associated with fossil mineral deposits, not fossil fuel combustion.

References: C-2, C-7, and C-9.

Source: Franklin Associates, A Division of ERG

Cullet (In-House)

Cullet is imperfect articles of glass, trim, or other glass pieces that are melted and used in new glass products. In-house cullet is melted in a glass furnace in a manner similar to the virgin inputs to a conventional batch operation. It is widely recognized that cullet melts at a lower temperature than virgin glass materials. Because the glass furnace accounts for a large portion of the manufacturing energy for the container, any energy savings in the furnace can significantly affect the total energy demand. Cullet generated in-house is returned to the furnace, and accounts for approximately 8 percent of the total raw material requirements with an estimated 10 percent loss of material (Reference C-6).

Cullet (Postconsumer)

Although in-house scrap has been the major source of cullet for many plants, mandatory deposit conditions and more active collection programs have increased the amount of postconsumer cullet recovered. Postconsumer cullet must be recovered, sorted, and crushed before it is added to the virgin material.

Recovery. Postconsumer glass containers are typically recovered in municipal recycling programs. Consumers leave used containers either at drop-off sites or at the curb for curbside pickup.

Sorting and Crushing. Postconsumer glass is typically sorted by color and then crushed in order to densify it for more economical transportation to glass plants. Theoretically, a glass plant can produce new containers entirely from cullet; however, no plants currently operate at this level.

Substantial amounts of postconsumer cullet can be used if it meets the standards for purity and color. Although cullet specifications vary by company, the industry uses the ASTM standards as a basis. The ASTM requirements do allow some color mixing; however, glass plants typically request color separation of incoming cullet. This allows the glass plant to control the level of color mixing. Many glass plants are now investing in expensive front-end beneficiation systems which remove contaminants from postconsumer containers and provide the plant with furnace-ready cullet. As more glass plants incorporate this capability, processing problems for recyclers of glass will be slightly alleviated, and an increase in material processing may be observed. Processing recovered glass bottles involves sorting by color, crushing, and shipping to a glass plant.

Cullet is added to the glass furnace along with the virgin inputs to a conventional batch operation. The composition of glass varies by type. For instance, container glass (used for food and beverage containers) has a different composition from plate or flat window glass. Therefore, only compatible cullet may be used in a furnace.

Typical losses from the recovery system are 10 percent of the material recovered. The energy requirements and environmental emissions for the recovery, sorting and crushing of cullet are shown in Table C-23.

Table C-23

DATA FOR THE PROCESSING OF 1,000 POUNDS OF POSTCONSUMER CULLET

Process Energy			
Electricity (grid)	32.3	kwh	332
Total Process			332
Transportation Energy			
Combination truck	50.0	ton-miles	
Diesel	0.53	gal	83.4
Rail	100	ton-miles	
Diesel	0.25	gal	39.4
Total Transportation			123
Environmental Emissions			
Solid Wastes	73.9	lb	

References: C-10, C-11, and C-17.

Source: Franklin Associates, A Division of ERG

Glass Container Manufacture

Glass is manufactured by mixing glass sand, limestone, soda ash, feldspar, small amounts of other minerals and cullet into a homogenous mixture, which is then fed to the melting furnace. This is typically a natural gas-fired, continuous melting, regenerative furnace. Fuel is conserved by using brick checkers to collect furnace exhaust gas heat, then using the hot checkers to preheat the furnace combustion air. The molten glass is directed to forming machines where it is cut into sections called gobs and shaped into containers. The container undergoes finishing, annealing, inspection, and then preparation for shipment.

The melting furnace contributes over 99 percent of the total air emissions from a glass plant, including particulates, sulfur oxides, nitrogen oxides, volatile organic compounds, and carbon monoxide. Particulates and selenium result from the volatilization of materials during the melting operation which then combine with gases and form condensates. Sulfur oxides are produced from the decomposition of the sulfates in the feed and sulfur in the fuel. Nitrogen oxides form when nitrogen and oxygen react in the scrubbers. High energy venturi scrubbers, baghouses, and electrostatic precipitators have been used to collect the particulates and sulfur oxides.

Most of the water used in glass manufacturing is used in coolers and boilers and is therefore not in direct contact with the glass. Water used in washing and quenching of the glass does come into direct contact and is contaminated with oil and grease from the forming machine lubricant. Grease and oil lubricants are being replaced by silicone emulsions and water-soluble oils, which has decreased the oil and grease contamination.

The energy requirements and emissions for the manufacture of virgin glass containers are shown in Table C-24. The energy and emissions data for the manufacture of recycled glass containers are shown in Table C-25. The average glass containers in this study are made with 27 percent postconsumer cullet (Reference C-1).

Table C-24

**DATA FOR THE PRODUCTION
OF 1,000 POUNDS OF VIRGIN GLASS CONTAINERS**

Raw Materials			
Limestone	158	lb	
Glass sand	667	lb	
Soda ash	208	lb	
Feldspar	69	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	70.1	kwh	721
Natural gas	2,331	cu ft	2,611
Distillate oil	2.00	gal	318
Residual oil	1.80	gal	309
Total Process			3,959
Transportation Energy			
Combination truck	180	ton-miles	
Diesel	1.89	gal	300
Rail	20.0	ton-miles	
Diesel	0.050	gal	7.88
Total Transportation			308
Environmental Emissions			
Atmospheric Emissions			
Particulates	0.10	lb	
Sulfur oxides	0.50	lb	
Carbon dioxide, fossil*	158	lb	
Selenium	0.0040	lb	
Nitrogen oxides	2.80	lb	
Solid Wastes	22.5	lb	
Waterborne Wastes			
Suspended solids	0.070	lb	

*Carbon dioxide releases associated with fossil mineral inputs, not fossil fuel combustion.

References: C-13, C-14, C-16, C-19, and C-20.

Source: Franklin Associates, A Division of ERG

Table C-25

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF RECYCLED GLASS CONTAINERS

Raw Materials			
Postconsumer cullet	1,023	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	56.0	kwh	576
Natural gas	1,747	cu ft	1,957
Distillate oil	1.60	gal	254
Residual oil	1.40	gal	240
Total Process			3,027
Transportation Energy			
Combination truck	180	ton-miles	
Diesel	1.89	gal	300
Rail	20.0	ton-miles	
Diesel	0.050	gal	7.88
Total Transportation			308
Environmental Emissions			
Atmospheric Emissions			
Particulates	0.10	lb	
Sulfur Oxides	0.50	lb	
Selenium	0.0040	lb	
Nitrogen Oxides	2.80	lb	
Solid Wastes			
Landfilled	22.5	lb	
Waterborne Wastes			
Suspended solids	0.0070	lb	

References: C-13, C-14, C-16, C-17, and C-20.

Source: Franklin Associates, A Division of ERG

VIRGIN ALUMINUM

The steps for the production of virgin aluminum, also known as primary aluminum, are as follows:

- Salt Mining
- Caustic Soda Production
- Limestone Mining
- Lime Production
- Bauxite Mining
- Alumina Production
- Coal Mining
- Metallurgical Coke Production
- Crude Oil Production
- Petroleum Coke Production
- Anode Production
- Aluminum Smelting
- Aluminum Ingot Casting

Coal mining, crude oil production, and limestone mining are discussed previously in this appendix and are not repeated in this section. The remaining processes of primary aluminum production are discussed below.

There are no coproducts from primary aluminum production. Aluminum scrap may result from aluminum ingot casting, the final step of primary aluminum production, but it is easily recycled within the system. Thus, coproduct allocation is not necessary for this appendix.

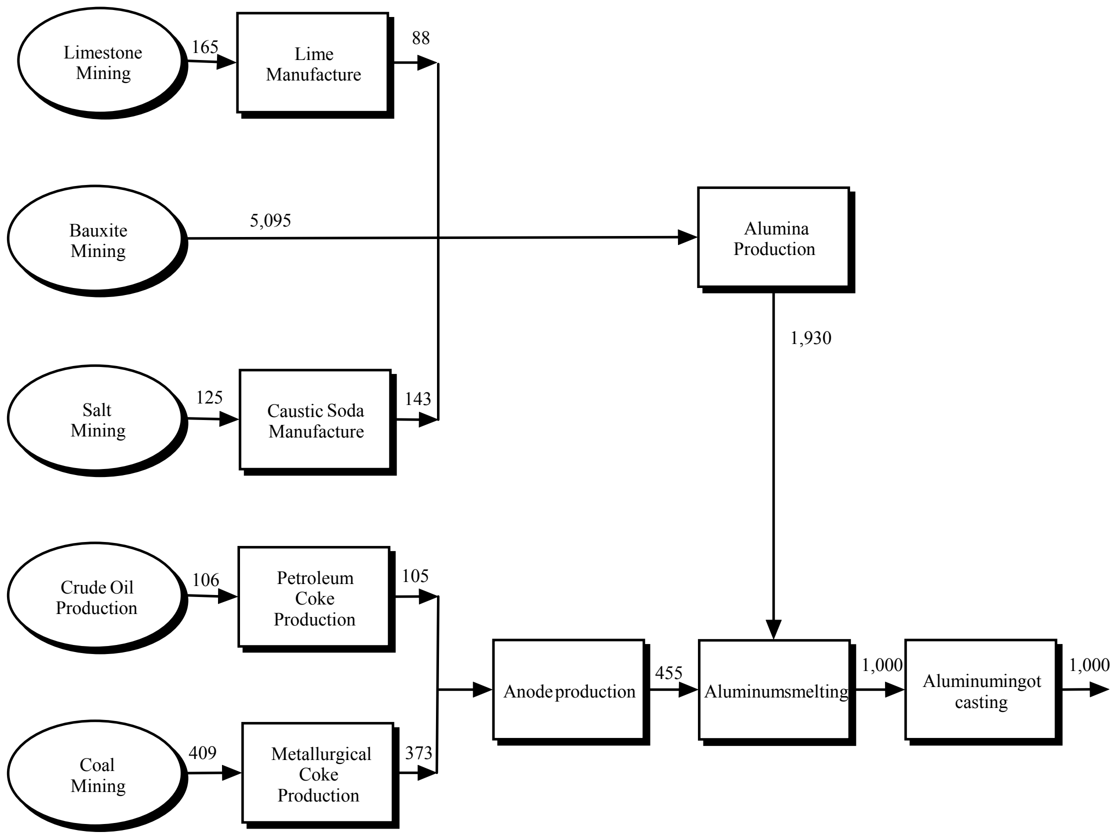

Figure C-7: Flow diagram for primary aluminum production

Salt Mining

For the most part, salt-based chlorine and caustic facilities use captive salt from another process or use salt recovered from underground deposits in the form of brine. In solution mining, an injection well is drilled and pressurized fresh water is introduced to the bedded salt (Reference C-63). The brine is then pumped to the surface for treatment. Salt mines are widely distributed throughout the United States.

No data are available for the energy requirements of the solution mining of salt brine in the United States. European data (Reference C-62) developed by APME (Association of Plastics Manufacturers in Europe) were used to represent United States salt production. The APME data represent solution mining and brine purification technologies, which are the predominant technologies used for salt production in the United States.

No data are available for air emissions from salt mining. Since salt mining involves no chemical reactions and minimal processing requirements, it is assumed that negligible process emissions result from salt mining.

TSS (total suspended solids) are the only BPT (best practicable technology) limited water effluent from sodium chloride production (Reference C-64). No data are available for other water effluents. However, BPT limitations for sodium chloride production by solution mining stipulate that no process wastewater is returned to navigable waters. Any solution remaining after the recovery of salt brine can be returned to the body of water or salt deposit from which it originally came (Reference C-59).

Salt deposits are relatively pure and require minimal beneficiation (Reference C-57). Any overburden that may be removed during rock salt mining can be returned to the mining site after the salt is recovered. Similarly, solution mining is a technology that does not generate significant amounts of solid wastes. It is thus assumed that salt mining produces negligible quantities of solid waste. Data for salt mining are shown in Table C-26.

Table C-26

DATA FOR THE MINING OF 1,000 POUNDS OF SALT

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	15.1	kwh	161
Natural Gas	397	cu ft	445
Coal	11.7	lb	131
Distillate Oil	1.21	gal	192
Total Process			929
Transportation Energy			
Rail	1.25	ton-miles	
Diesel	0.0031	gal	0.49
Barge	1.25	ton-miles	
Diesel	0.0010	gal	0.16
Residual Oil	0.0033	gal	0.57
Pipeline-Petroleum Products	114	ton-miles	
Electricity	2.49	kwh	25.5
Total Transportation			26.7

References: C-57 through C-64.

Source: Franklin Associates, A Division of ERG

Caustic Soda (Sodium Hydroxide) Production

Caustic soda (sodium hydroxide) and chlorine are produced from salt by an electrolytic process. Aqueous sodium chloride solution is electrolyzed to produce caustic soda, chlorine, and hydrogen gas.

There are three commercial processes for the electrolysis of sodium chloride: (1) the diaphragm cell process, (2) the mercury cathode cell process, and (3) the membrane cell process. Diaphragm cell electrolysis is used for 71 percent of production, mercury cathode cell electrolysis is used for 12 percent of production, and membrane cell electrolysis is used for 16 percent of production (Reference C-66). Membrane cell electrolysis is a new technology that is gradually gaining commercial acceptance. Membrane cell electrolysis has relatively low energy requirements, but its high capital costs have hindered its growth (Reference C-66). No data are available for membrane cell electrolysis; this appendix thus assigns 85 percent of chlorine and caustic soda production to diaphragm cell electrolysis and 15 percent of chlorine and caustic soda production to mercury cathode cell electrolysis (Reference C-67).

The diaphragm cell uses graphite anodes and steel cathodes. Brine solution is passed through the anode compartment of the cell, where the salt is decomposed into chlorine gas and sodium ions. The gas is removed through a pipe at the top of the cell. The sodium ions pass through a cation-selective diaphragm. The depleted brine is either resaturated with salt or concentrated by evaporation and recycled to the cell. The sodium ions transferred across the diaphragm react at the cathode to produce hydrogen and sodium hydroxide. Diffusion of the cathode products back into the brine solution is prevented by the diaphragm.

The mercury cell uses graphite anodes and mercury cathodes. Sodium reacts with the mercury cathode to produce an amalgam (an alloy of mercury and sodium) that is sent to another compartment of the cell and reacted with water to produce hydrogen and high purity sodium hydroxide. The chemistry that occurs at the mercury cathode includes the following reactions:

$$NaCl + xHg \rightarrow 1/2\ Cl_2 + Na(Hg)_x \quad \text{and}$$
$$Na(Hg)_x + H_2O \rightarrow NaOH + 1/2\ H_2 + xHg$$

Mercury loss is a disadvantage of the mercury cathode cell process. Some of the routes by which mercury can escape are in the hydrogen gas stream, in cell room ventilation air and washing water, through purging of the brine loop and disposal of brine sludges, and through end box fumes.

Titanium anodes, coated with metal oxide finishes, are gaining commercial acceptance and are gradually replacing graphite anodes. The advantages of titanium anodes are (1) corrosion resistance and (2) the low activation energy for electrolysis at the anode surface (Reference C-65).

It is not possible, using the electrolytic cell, to get chlorine from salt without also producing sodium hydroxide and hydrogen, both of which have commercial value as useful coproducts. Likewise, sodium hydroxide cannot be obtained without producing the valuable coproducts of chlorine and hydrogen. Furthermore, it is not possible to control the cell to increase or decrease the amount of chlorine or caustic soda resulting from a given input of salt. This is determined by the stoichiometry of the reaction; the electrolysis of sodium chloride produces approximately 1.1 tons of 50 percent caustic soda solution per ton of chlorine. A mass basis is used for allocating process burdens to the coproducts. The mass allocation approach is used consistently in this analysis as the basis for coproduct allocations for other processes that produce mass quantities of more than one useful output product. Data for production of chlorine or caustic from salt are shown in Table C-27.

Lime Production

Lime is never found in a natural state, but is manufactured by calcining (burning) high purity calcitic or dolomitic limestone at high temperatures. The calcination process drives off carbon dioxide, forming calcium oxide (quicklime). The subsequent addition of water creates calcium hydroxide (hydrated or slaked lime).

Lime is a class of various chemical and physical forms of quicklime and hydrated lime. The majority of lime produced in the United States is quicklime (Reference C-70). The data in this appendix represent the calcining of limestone to produce calcium oxide (quicklime); the subsequent production of calcium hydroxide is not included in this appendix.

Energy data for the production of lime shown in Table C-28 are based on U.S. manufacturing surveys (Reference C-71).

Solid wastes generated during the production of lime include impurities removed from the limestone, tailings collected in the lime production process, and lime kiln dust collected from particulate control devices on the lime kilns. Based on lengthy discussions with a confidential industry representative, it was assumed that all collected lime dust and tailings from lime production are either sold for various useful purposes, injected back into mines, replaced in quarries, or land applied on site. Packaging and other industrial wastes from lime production are disposed in a municipal landfill (References C-68 and C-69).

Table C-27

DATA FOR THE PRODUCTION OF
1,000 POUNDS OF CHLORINE OR CAUSTIC SODA

Raw Materials			
Salt Mining	877	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	477	kwh	5,074
Natural Gas	1,711	cu ft	1,916
Coal	24.4	lb	274
Residual Oil	23.3	gal	3,998
Total Process			11,262
Transportation Energy			
Combination Truck	24.6	ton-miles	
Diesel	0.26	gal	41.0
Rail	66.5	ton-miles	
Diesel	0.16	gal	26.2
Pipeline-Petroleum Products	2.60	ton-miles	
Electricity	0.057	kwh	0.58
Total Transportation			67.8
Environmental Emissions			
Atmospheric Emissions			
Carbon Monoxide	1.2E-04	lb	
Chlorine	0.0011	lb	
CO2 Fossil	0.064	lb	
HCl	2.8E-04	lb	
HFC/HCFC	1.5E-04	lb	
Hydrocarbons (unspecified)	2.3E-04	lb	
Lead	9.6E-09	lb	
Methane	9.2E-07	lb	
Mercury	2.8E-04	lb	
Nitrogen Oxides	0.0033	lb	
Other Organics	2.6E-05	lb	
Particulates (unspecified)	0.0026	lb	
PM2.5	1.0E-04	lb	
PM10	0.018	lb	
Sulfur Oxides	4.7E-04	lb	
Solid Wastes			
Landfilled	2.94	lb	
Waterborne Wastes			
BOD	0.23	lb	
Copper	1.1E-07	lb	
Dissolved Solids	38.2	lb	
Lead	4.9E-07	lb	
Mercury	7.8E-07	lb	
Nickel	5.0E-07	lb	
Sulfides	7.8E-05	lb	
Suspended Solids	0.069	lb	
Zinc	4.9E-07	lb	

References: C-58, C-59, C-66, and C-89.

Source: Franklin Associates, A Division of ERG

Table C-28

**DATA FOR THE PRODUCTION OF
1,000 POUNDS OF LIME**

			Total Energy Thousand Btu
Raw Materials			
Limestone Mining	1,875	lb	
Energy Usage			
Process Energy			
Electricity	30.7	kwh	327
Natural Gas	337	cu ft	377
LPG	0.0039	gal	0.42
Coal	172	lb	1,932
Distillate Oil	0.11	gal	17.5
Total Process			2,653
Transportation Energy			
Combination Truck	25.0	ton-miles	
Diesel	0.26	gal	41.7
Rail	5.00	ton-miles	
Diesel	0.012	gal	1.97
Barge	7.50	ton-miles	
Diesel	0.0060	gal	0.95
Residual Oil	0.020	gal	3.42
Total Transportation			48.0
Environmental Emissions			
Atmospheric Emissions			
Carbon dioxide, fossil*	768	lb	
Particulates (unspecified)	0.056	lb	
Sulfur Oxides	0.15	lb	
Solid Wastes			
Landfilled	5.00	lb	

*Carbon dioxide releases from calcified fossil material in limestone, not fossil fuel combustion.

References: C-92 through C-94

Source: Franklin Associates, A Division of ERG

Bauxite Mining

Aluminum is the most widely distributed metal in the earth's crust, with only the nonmetallic elements oxygen and silicon surpassing it in abundance. However, bauxite ore is the only commercially exploited source of aluminum. Although other types of earth, including ordinary clay, contain aluminum, economics favor the use of bauxite.

Bauxite is formed by the action of rain and erosion on materials containing aluminum oxide (alumina). The heavy rainfall and warm temperatures of the tropics provide nearly ideal conditions for this process, and most of the world's bauxite is mined in these regions. Australia is the leading producer of bauxite, followed by Guinea, Jamaica, Brazil, and Guyana (Reference C-23). Over 99 percent of the total bauxite imported by the U.S. is supplied by these countries. This analysis assumes that the European supply of bauxite is similar to that of the U.S.

Electricity Generation for Bauxite Mining. In order to calculate the fuels used to generate electricity for bauxite production, it is necessary to determine the percent of bauxite produced in each of the aforementioned countries. This quantity is calculated from the amount exported to the U.S. as bauxite ore and the amount used within each country to produce alumina, which is then exported to the U.S.

Approximately 48 percent of the alumina consumed by U.S. smelters is produced domestically from imported bauxite (Reference C-23). The remaining 52 percent of the U.S. alumina supply is imported mostly from Australia, Jamaica, Suriname, and Brazil. (As was the case with bauxite imports, this analysis assumes that sources of European alumina are similar to sources of U.S. alumina.) In order to equate the amount of bauxite required for the production of imported alumina, a factor of 2.6 pounds of bauxite per pound of alumina was used (Reference C-21). Based on import statistics (Reference C23) and the above assumptions, the alumina consumed in North America (including domestically-produced and imported alumina) originates from bauxite produced in the following countries: Australia (2 percent), Jamaica (55 percent), Guinea (30 percent), Brazil (3 percent), Suriname (1 percent), and Guyana (9 percent). No country-specific data on bauxite mining emissions were available; therefore data for U.S. bauxite mining are used. In the life cycle model, the energy and emissions for electricity use in bauxite production is a weighted average calculated based on the percentage of bauxite produced by each country and the mix of fuels used for electricity production in that country. Bauxite production data are shown in Table C-29.

Table C-29

DATA FOR THE MINING OF 1,000 POUNDS OF BAUXITE

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	0.18	kwh	1.91
Residual Oil	0.15	gal	25.7
Gasoline	0.032	gal	4.55
Diesel	0.52	gal	82.6
Total Process			115
Transportation Energy			
Rail	109	ton-miles	
Diesel	0.27	gal	42.9
Ocean Freighter	877	ton-miles	
Diesel	0.17	gal	26.5
Residual	1.50	gal	257
Total Transportation			327

Environmental Emissions

Atmospheric Emissions		
Carbon Monoxide	0.0032	lb
Carbon dioxide, fossil	0.79	lb
Hydrocarbons (unspecified)	4.5E-04	lb
Methane	0.0066	lb
Nitrous Oxide (N2O)	3.4E-04	lb
Nitrogen Oxides	0.040	lb
Particulates (unspecified)	2.35	lb
Sulfur Oxides	0.0011	lb
Solid Wastes		
Landfilled	136	lb
Waterborne Wastes		
Detergents	2.5E-06	lb
Dissolved Solids	2.1E-04	lb
Nitrogen	6.5E-07	lb
Oil	1.9E-06	lb
Phosphates	2.5E-06	lb
Suspended Solids	1.5E-05	lb

References: C-21

Source: Franklin Associates, A Division of ERG

Alumina Production

Before it can be used in the manufacture of metallic aluminum, bauxite ore must be refined to nearly pure aluminum oxide, usually called alumina. The Bayer process is the preferred method for bauxite refining. Bauxite is crushed and dissolved in digesters using strong caustic soda and lime solution. The undissolved residue, known as red mud, is filtered out. Sodium aluminate remains in solution, where it is hydrolyzed and precipitated as aluminum hydroxide, which is then calcined to alumina in a rotary kiln. Red mud filtered from the digester liquid is considered solid waste in this analysis. Red mud production rates vary depending on the quality of the ore and the level of alumina recovery.

Electricity Generation for Alumina Production. Primary fuels for electricity generation for alumina that is consumed by the U.S. are calculated based on the countries producing the alumina.

As stated earlier, 52 percent of alumina consumed in the U.S. is imported. Australia, Jamaica, Suriname, and Brazil produce the majority of this alumina. Based on import statistics, 32 percent of alumina imported by the U.S. comes from Australia, 5 percent comes from Jamaica, 13 percent comes from Suriname, and 1 percent comes from Brazil. Primary fuels used for electricity generation in these countries were calculated from worldwide energy data available from the U.S. EIA (Reference C-22).

Primary fuels used to generate electricity for alumina production facilities in the U.S. are calculated from the fuel mix for the North American Electricity Reliability Council (NERC) regional electricity grid in which the plants are located. Approximately 69 percent of the U.S. alumina production capacity is in the Electric Reliability Council of Texas (ERCOT) and the remaining 31 percent is in the Southwest Power Pool (SPP) (References C-37 and C-38). Therefore, 33 percent of the total alumina used is produced in the ERCOT region and 17 percent is produced in the SPP region. The fuel mix of each NERC region is detailed in U.S. EPA's eGRID database (Reference C-25). Alumina production data are presented in Table C-30.

Table C-30

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF ALUMINA

			Total Energy Thousand Btu
Raw Materials			
Sodium Hydroxide Manufacture	73.9	lb	
Lime Production	45.7	lb	
Bauxite Mining	2,640	lb	
Energy Usage			
Process Energy			
Electricity	49.5	kwh	527
Natural Gas	3,606	cu ft	4,039
Coal	8.59	lb	96.5
Residual Oil	11.9	gal	2,042
Gasoline	0.0028	gal	0.40
Diesel	0.20	gal	31.8
Total Process			6,736
Transportation Energy			
Rail	152	ton-miles	
Diesel	0.38	gal	59.9
Ocean Freighter	878	ton-miles	
Diesel	0.17	gal	26.5
Residual	1.50	gal	257
Total Transportation			344
Environmental Emissions			
Atmospheric Emissions			
HCFC/HFCs	6.7E-07	lb	
Hydrocarbons (unspecified)	0.047	lb	
Mercury	2.1E-05	lb	
Methane	0.017	lb	
Nitrous Oxide (N2O)	2.2E-04	lb	
Particulates (unspecified)	0.45	lb	
Solid Wastes			
Landfilled	1,125	lb	
Waterborne Wastes			
Acid (unspecified)	0.061	lb	
BOD	6.1E-12	lb	
Calcium	0.0058	lb	
Chlorides	0.0076	lb	
COD	0.046	lb	
Dissolved Solids	0.010	lb	
Fluorine	7.9E-04	lb	
Iron	1.6E-05	lb	
Mercury	6.1E-07	lb	
Metal Ion (unspecified)	0.069	lb	
Oil	3.9E-04	lb	
Phenol/Phenolics	3.9E-07	lb	
Sodium	1.96	lb	
Sulfates	1.75	lb	
Suspended Solids	0.13	lb	

References: C-21

Source: Franklin Associates, A Division of ERG

Coal Mining

Coal may be obtained by surface mining of outcrops or seams that are near the earth's surface or by underground mining of deposits. In strip mining, the overburden is removed from shallow seams, the deposit is broken up, and the coal is loaded for transport. Generally, the overburden is eventually returned to the mine and is not considered as a solid waste in this analysis.

After the coal is mined, it goes through various preparation processes before it is used. These processes vary depending on the quality of the coal and the use for which it is intended. Coal preparation usually involves some type of size reduction and partial removal of ash-forming materials. Data for coal mining are shown in Table C-31.

Metallurgical Coke Production

The two proven processes for manufacturing metallurgical coke are known as the beehive process and the byproduct process (Reference C-31). The primary method for manufacturing coke is the byproduct method, which accounts for more than 98 percent of U.S. coke production (Reference C-31). For this analysis, it is assumed that all metallurgical coke is produced in the byproduct oven.

In the byproduct method, air is excluded from the coking chambers, and the necessary heat for distillation is supplied from external combustion of some of the gas recovered from the coking process (Reference C-32). Coking 1,000 pounds of coal in the byproduct oven is produces the following: coke, 774 lb; tar, 37 lb; water, 32 lb; benzene, 11 lb; and coke oven gas, 147 lb (Reference C-32). Coproduct credit is given on a weight basis to all of the outputs from the oven, except water. It is estimated that about 40 percent of the coke oven gas (59 pounds) is used as a fuel for underfiring the coke oven (Reference C-31). Therefore, coproduct credit is given for the remaining 88 lb of coke oven gas. The total net mass of coproducts from coking is thus (774 + 37 + 11 + 88) = 910 lb of coproducts per 1,000 lb of coal input, or 1,000/910 = 1.099 lb of coal per lb of coproduct.

In the coke oven, the coal serves both as a material input and a source of energy. The energy derived from the coal is not shown separately in Table C-32 but is calculated in the LCI model based on the energy content of the coal material input to the coking process.

Table C-31

DATA FOR THE MINING OF 1,000 POUNDS OF COAL

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	17.6	kwh	187
Natural gas	2.59	cu ft	2.90
LPG	0	gal	0
Coal	0.13	lb	1.46
Distillate oil	1.05	gal	167
Residual oil	0.10	gal	17.2
Gasoline	0.10	gal	14.2
Diesel	0	gal	0
Total Process			390
Transportation Energy			
Combination truck	2.14	ton-miles	
Diesel	0.022	gal	3.57
Rail	324	ton-miles	
Diesel	0.80	gal	128
Barge	39.3	ton-miles	
Diesel	0.031	gal	4.99
Residual oil	0.10	gal	17.9
Pipeline-coal slurry	1.56	ton-miles	
Electricity	0.37	kwh	3.83
Total Transportation			158
Environmental Emissions			
Atmospheric Emissions			
Particulates (unspecified)	1.63	lb	
Methane	3.99	lb	
VOC	0.026	lb	
Solid Wastes			
Landfilled	235	lb	
Waterborne Wastes			
Suspended Solids	0.10	lb	
Iron	0.0086	lb	
Manganese	0.0058	lb	

Source: Franklin Associates, A Division of ERG

Table C-32

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF METALLURGICAL COKE

Raw Materials			
Coal Mining	1,099	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	17.6	kwh	187
Total Process			187
Environmental Emissions			
Atmospheric Emissions			
Ammonia	0.080	lb	
Carbon Monoxide	0.73	lb	
Carbon dioxide, fossil*	130	lb	
Hydrocarbons (unspecified)	3.17	lb	
Nitrogen Oxides	0.77	lb	
Particulates (unspecified)	1.42	lb	
Sulfur Oxides	4.00	lb	
Solid Wastes			
Landfilled	4.00	lb	
Waterborne Wastes			
Ammonia	0.0032	lb	
Cyanide	0.0034	lb	
Dissolved Solids	0.089	lb	
Phenol/Phenolics	0.0015	lb	
Suspended Solids	6.0E-04	lb	

*Carbon dioxide releases associated with coke oven gas generated and used within the process.

References: C-30 through C-35

Source: Franklin Associates, A Division of ERG

Petroleum Coke Production

Petroleum coke is used in the manufacture of carbon electrodes, which are used in the electrolytic reduction of alumina to aluminum. Coking is an extreme form of thermal cracking that uses high temperatures and long residence times to break down heavy crude residues to lighter liquids (Reference C-28). Coking takes place in a series of ovens in the absence of oxygen. After a typical coking time of 12 to 20 hours, most of the volatile matter is driven from the crude residue and the coke is formed. The desired products of the coking process are actually the volatile products. The petroleum coke itself is considered a byproduct. The coke is collected in a coke drum, while the lighter products go overhead as vapors. Data for the production of petroleum coke are shown in Table C-33.

Anode Production

The two types of aluminum smelting technologies are distinguished by the type of anode that is used in the reduction process: soderberg and prebake. Soderberg design has a single anode that covers most of the top surface of a reduction cell (pot). Anode paste (briquettes) is fed to the top of the anode and as the anode is consumed in the process, the paste feeds downward by gravity. Heat from the pot bakes the paste into a monolithic mass before it gets to the electrolytic bath interface. The prebake design has prefired blocks of solid carbon suspended from axial busbars. The busbars both hold the anodes in place and carry the current for electrolysis.

The process for making the aggregate for briquettes or prebake blocks is identical. Coke is calcined, ground and blended with pitch to form a paste that is subsequently extruded into blocks or briquettes and allowed to cool. While the briquettes are sent direct to the pots for consumption, the blocks are then sent to a separate baking furnace.

Baking furnace technology has evolved from simple pits that discharged volatiles to atmosphere during the baking cycle to closed loop type designs that convert the caloric heat of the volatile into a process fuel that reduces energy consumption for the process.

Data for the production of anodes from coke are shown in Table C-34.

Table C-33

**DATA FOR THE PRODUCTION OF
1,000 POUNDS OF PETROLEUM COKE**

			Total Energy Thousand Btu
Raw Materials			
Crude Oil Production	1,005	lb	
Energy Usage			
Process Energy			
Electricity	16.1	kwh	171
Natural Gas	872	cu ft	977
LPG	0.25	gal	27.0
Residual Oil	1.75	gal	278
Total Process			1,453
Transportation Energy			
Rail	660	ton-miles	
Diesel	1.64	gal	260
Total Transportation			260
Environmental Emissions			
Atmospheric Emissions			
Aldehydes (unspecified)	0.040	lb	
Ammonia	0.0053	lb	
Chlorine	2.1E-04	lb	
HCl	1.6E-04	lb	
Hydrocarbons (unspecified)	1.38	lb	
Lead	1.4E-06	lb	
Particulates (unspecified)	0.060	lb	
Sulfur Oxides	0.20	lb	
Solid Wastes			
Landfilled	3.36	lb	
Waterborne Wastes			
Acid (unspecified)	1.1E-06	lb	
Ammonia	0.0018	lb	
BOD	0.014	lb	
Chromium (unspecified)	4.5E-06	lb	
COD	0.066	lb	
Dissolved Solids	0.94	lb	
Iron	4.2E-04	lb	
Lead	2.0E-06	lb	
Metal Ion (unspecified)	0.024	lb	
Oil	8.1E-04	lb	
Phenol/Phenolics	7.8E-05	lb	
Suspended Solids	0.013	lb	
Zinc	3.0E-05	lb	

References: C-21

Source: Franklin Associates, A Division of ERG

Table C-34

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF ANODES

Raw Materials			
Metallurgical Coke	820	lb	
Petroleum Coke	231	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	121	kwh	1,285
Natural Gas	1,556	cu ft	1,743
LPG	0.14	gal	14.7
Residual Oil	0.59	gal	101
Gasoline	0.0054	gal	0.77
Diesel	0.013	gal	2.06
Total Process			3,146
Environmental Emissions			
Atmospheric Emissions			
Carbon Monoxide	2.07	lb	
Carbon dioxide, fossil*	388	lb	
NM Hydrocarbons	0.24	lb	
Nitrogen Oxides	0.11	lb	
Other Organics	0.0013	lb	
Particulates (unknown)	2.47	lb	
Hydrogen Fluoride	0.023	lb	
Polyaromatic Hydrocarbons (PAH)	0.014	lb	
Sulfur Oxides	3.22	lb	
Lead	4.5E-09	lb	
Metals (unspecified)	3.3E-05	lb	
Sulfuric Acid	0.0044	lb	
CFC/HCFC	1.1E-05	lb	
Solid Wastes			
Landfilled	24.4	lb	
Waterborne Wastes			
Ammonium Ion	1.5E-04	lb	
BOD	0.015	lb	
Chlorine	1.4E-06	lb	
COD	0.18	lb	
Cyanide	6.3E-07	lb	
Detergents	9.4E-06	lb	
Dissolved Organics	0.0039	lb	
Dissolved Solids	0.0023	lb	
Fluorides	0.013	lb	
Hydrocarbons	2.0E-05	lb	
Iron	4.2E-04	lb	
Lead	5.7E-06	lb	
Metal Ion (unspecified)	0.013	lb	
Phenol/Phenolics	2.3E-07	lb	
Nitrates	0.0016	lb	
Oil	0.012	lb	
Suspended Solids	0.043	lb	
Nitrogen	2.2E-05	lb	
Sulfate ion	0.023	lb	
Magnesium ion	0.0047	lb	

*Carbon dioxide releases from coke during anode production.

References: C-21

Source: Franklin Associates, A Division of ERG

Aluminum Smelting

Smelting is the reduction of refined alumina to metallic aluminum by the electrolytic separation of aluminum from its oxide. The process is carried out in a long series of electrolytic cells carrying direct current. The alumina is dissolved in a molten bath of cryolite (an electrolyte) and aluminum fluoride (which increases the conductivity of the electrolyte). These chemicals are assumed to be recovered with little or no loss, and therefore negligible inputs of these materials are assumed for this LCI. Carbon anodes carry the current to the solution, and on to the next cell. The anodes are consumed during the reaction at a rate of 455 pounds of material per 1,000 pounds of aluminum produced. The principal products of the reaction are carbon dioxide, which is released as a gas, and elemental aluminum, which settles to the bottom of the cell and is periodically drained off.

Electricity Generation for Aluminum Smelting. Aluminum smelting is based upon an electrolytic process; therefore, a relatively large quantity of electricity is used to produce primary aluminum, as shown in Table C-35. According to IPAI 2002 statistics (Reference C-24), the electricity profile for North American (Canada and the U.S.) smelters consists of the following fuels: hydro, 63.9%; coal, 34.6%; oil, 0.1%; natural gas, 0.4%; and nuclear, 0.9%. Of this electricity, 35.2% is self-generated and 64.8% is purchased.

Aluminum Ingot Casting

Molten aluminum is discharged from a smelter into the holding and ingot casting facility. In this step, molten metal is typically combined with high quality, in-house scrap and then cast into aluminum ingots (References C-26 and C-27). A melt loss occurs when dross is skimmed off the molten aluminum. The electricity for ingot casting shown in Table C-36 is assumed to be produced by the same fuel mix used for aluminum smelting because smelting and ingot casting usually occur in the same facility.

Table C-35

**DATA FOR THE SMELTING OF
1,000 POUNDS OF VIRGIN ALUMINUM**

Raw Materials			
Alumina Production	1,930	lb	
Anode Production	455	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	6,990	kwh	74,353
Natural Gas	122	cu ft	137
LPG	0.60	gal	64.9
Residual Oil	0.55	gal	94.4
Gasoline	0.034	gal	4.83
Diesel	0.22	gal	34.9
Total Process			74,688
Environmental Emissions			
Atmospheric Emissions			
Carbon Monoxide	66.9	lb	
Carbon dioxide, fossil*	1,520	lb	
COS	1.12	lb	
HCFC/HFCs	0.12	lb	
Hydrocarbons (unspecified)	0.91	lb	
Hydrogen Cyanide	0.037	lb	
Hydrogen Fluoride	0.62	lb	
Nitrogen Oxides	0.11	lb	
Particulates (unspecified)	4.75	lb	
PFC (perfluorocarbons)	0.38	lb	
Polyaromatic Hydrocarbons (PAH)	0.15	lb	
Sulfur Oxides	17.0	lb	
Solid Wastes			
Landfilled	59.4	lb	
Waterborne Wastes			
Ammonium Ion	5.7E-04	lb	
BOD	0.0091	lb	
Chlorides	0.0084	lb	
COD	0.079	lb	
Cyanide	2.0E-04	lb	
Detergents	5.9E-04	lb	
Dissolved Organics	0.013	lb	
Dissolved Solids	0.076	lb	
Fluorides	0.051	lb	
Hydrocarbons	4.8E-06	lb	
Iron	0.0022	lb	
Lead	4.6E-06	lb	
Mercury	4.0E-07	lb	
Metal Ion (unspecified)	0.0082	lb	
Nitrates	4.9E-04	lb	
Oil	0.010	lb	
Phenol/Phenolics	1.8E-04	lb	
Sodium	0.0062	lb	
Suspended Solids	0.060	lb	

*Carbon dioxide releases associated with consumption of the coke anodes within the process.

References: C-21

Source: Franklin Associates, A Division of ERG

Table C-36

DATA FOR THE CASTING OF
1,000 POUNDS OF ALUMINUM INGOT

			Total Energy Thousand Btu
Raw Materials			
Aluminum Smelting	1,000	lb	
Energy Usage			
Process Energy			
Electricity	95.8	kwh	1,019
Natural Gas	830	cu ft	930
LPG	0.18	gal	19.5
Residual Oil	2.23	gal	383
Gasoline	0.0088	gal	1.25
Diesel	0.022	gal	3.49
Total Process			2,355
Environmental Emissions			
Atmospheric Emissions			
Carbon Monoxide	0.0060	lb	
Chlorine	0.018	lb	
CO_2 (fossil)	0.93	lb	
Fluorine	0.019	lb	
HCl	0.053	lb	
Hydrocarbons (unspecified)	0.0038	lb	
Hydrogen Fluoride	0.0023	lb	
Lead	9.4E-06	lb	
Metals	0.0016	lb	
Nitrogen Oxides	0.026	lb	
Other Organics	0.011	lb	
Particulates (unspecified)	0.058	lb	
Sulfur Oxides	0.011	lb	
Solid Wastes			
Landfilled	21.2	lb	
Waterborne Wastes			
Ammonium Ion	3.6E-04	lb	
BOD	0.041	lb	
Chlorides	0.0079	lb	
COD	0.21	lb	
Cyanide	1.7E-06	lb	
Detergents	1.5E-05	lb	
Dissolved Organics	0.013	lb	
Dissolved Solids	0.18	lb	
Fluorides	0.0027	lb	
Iron	8.6E-04	lb	
Lead	3.2E-06	lb	
Mercury	1.4E-08	lb	
Metal Ion (unspecified)	0.0026	lb	
Oil	0.023	lb	
Phenol/Phenolics	1.2E-06	lb	
Sulfur	5.7E-04	lb	
Suspended Solids	0.067	lb	

References: C-21

Source: Franklin Associates, A Division of ERG

STEEL PRODUCTION

The production of steel via the basic oxygen furnace (BOF) route includes the following steps:

- Limestone Mining
- Lime Production
- Iron Ore Mining
- Coal Mining
- Metallurgical Coke Production
- Oxygen Manufacture
- Agglomerates Manufacture (Pellet and Sinter Production)
- External Scrap Procurement
- Pig Iron Production (Blast Furnace)
- Basic Oxygen Furnace

Limestone mining, lime production, coal mining, metallurgical coke production and oxygen manufacture are discussed in previously in this appendix and are not repeated in this section. The remaining steps of BOF steel production are discussed below.

The flows of materials among the unit processes of BOF steel production are shown in Figure C-8.

Iron Ore Mining

The basic raw material for steel manufacture is iron ore. This material is usually found in flat-lying or gently sloping beds not more than 20 feet thick. Open pit mining accounts for 90 percent of the iron ore extracted at present, with the remainder being recovered from deep vertical shaft mines. Overburden and waste rock from mining are eventually returned to the mine and are not considered solid waste in this analysis.

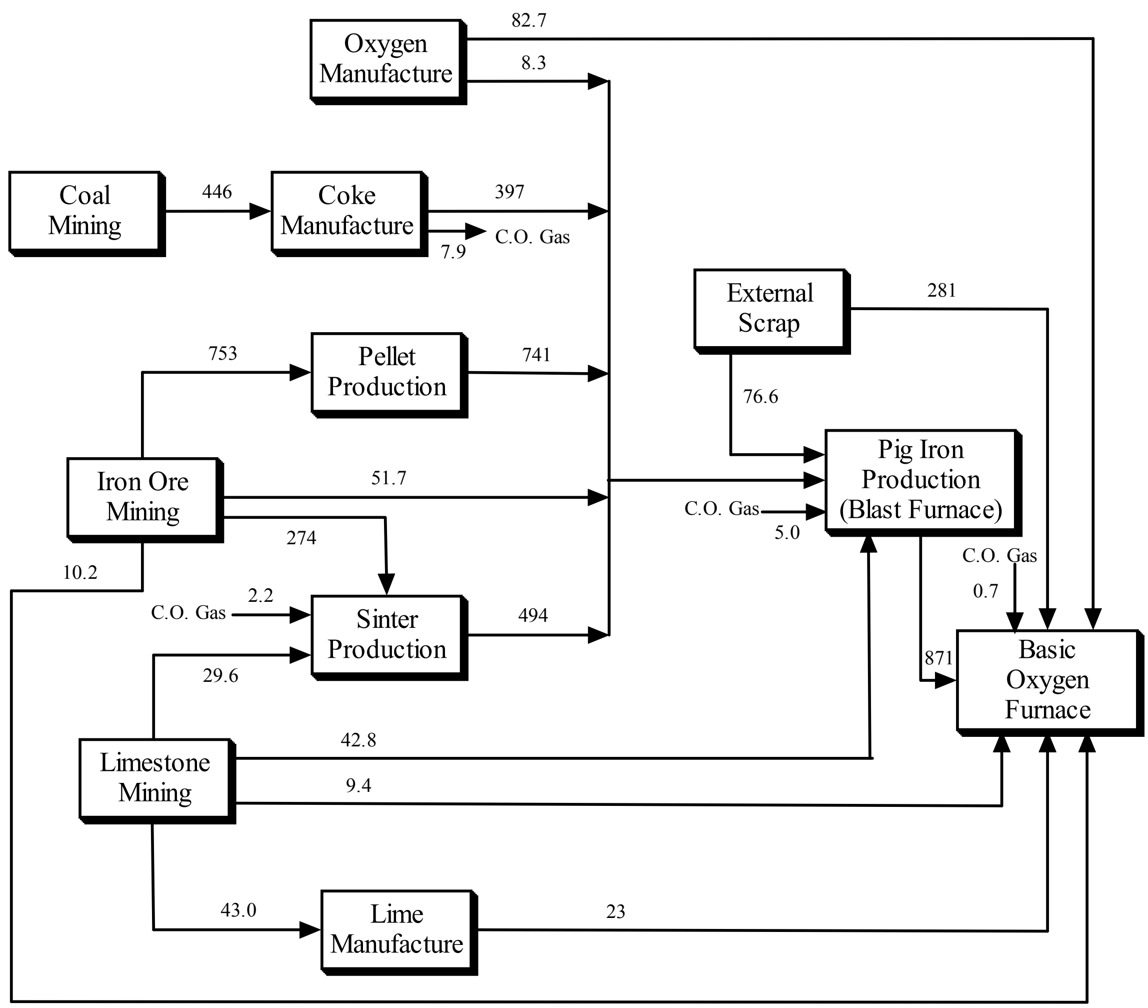

Figure C-8: Flow diagram for BOF steel production

Because of the stringent specifications placed on iron ore used in blast furnaces, it is necessary to beneficiate the ore. Beneficiation consists of crushing and grinding, screening, magnetic separation and other concentrating techniques. During beneficiation, a large quantity of tailings (liquid sludges from the concentration operations) are produced, approximately 2,181 pounds of ore tailings per 1,000 pounds of refined ore (Reference C-37). These tailings are generally pumped back to the mine site and deposited in settling ponds. The water is often recovered for reuse in the beneficiation facility, or the ponds are eventually drained. In either case, the solids end up being returned to the earth rather than landfilled and therefore are not included in the solid wastes reported in Table C-37.

Table C-37

DATA FOR THE MINING OF 1,000 POUNDS OF IRON ORE

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	51.1	kwh	544
Natural gas	242	cu ft	271
Distillate oil	0.23	gal	36.5
Gasoline	0.0090	gal	1.28
Total Process			852
Transportation Energy			
Rail	42.0	ton-miles	
Diesel	0.10	gal	16.5
Barge	158	ton-miles	
Diesel	0.13	gal	20.1
Residual oil	0.42	gal	72.1
Total Transportation			109
Environmental Emissions			
Atmospheric Emissions			
Particulates (unspecified)	0.39	lb	
Solid Wastes			
Landfilled	5.00	lb	
Waterborne Wastes			

Source: Franklin Associates, A Division of ERG

References: C-2, C-7, C-31, C-157.

Agglomerates Manufacture

Approximately 96 percent of iron ore charged into a blast furnace enters not as raw ore, but as agglomerates. These agglomerates are most commonly in the form of pellets and sinter.

Pellets (Table C-38) are made from fine concentrates of iron ore mixed with a binder (usually bentonite). The amount of bentonite is small, approximately 14 to 22 pounds per ton of feed to the sintering process (Reference C-37). Because the quantity of bentonite is a very small percentage, and because no data are available on production of bentonite, the entire mass of sinter is modeled as iron ore fines. After formation, the pellets are rolled, then heated to remove moisture. This process is usually carried out at the mine site.

Sinter (Table C-39) is generally made at the iron or steel mill, and consists of iron ore fines, coke dust, mill scale, flue dust, etc., gathered from the steel-making process. The process also utilizes oxygen from air. The material inputs are heated on a grate to form sinter.

Table C-38

DATA FOR THE PRODUCTION OF
1,000 POUNDS OF PELLET (FOR STEEL MANUFACTURE)

Raw Materials			
Iron ore mining	1,015	lb	
Process Energy			
Electricity (grid)	2.24	kwh	23.8
Natural gas	127	cu ft	142
Distillate oil	0.69	gal	110
Total Process			276
Transportation Energy			
Environmental Emissions			
Atmospheric Emissions			
Particulates (unspecified)	1.60	lb	
Waterborne Wastes			
Suspended Solids	0.050	lb	

Source: Franklin Associates, A Division of ERG

References: C-31, C-33, and C-39.

Table C-39

DATA FOR THE PRODUCTION OF
1,000 POUNDS OF SINTER (FOR STEEL MANUFACTURE)

Raw Materials			
Limestone mining	60.0	lb	
Iron ore mining	550	lb	
Coke oven gas	4.50	lb	
Furnace slag (from blast furnace)	300	lb	
Oxygen (from air)	85.5	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	21.6	kwh	230
Total Process			230
Transportation Energy			
Environmental Emissions			
Atmospheric Emissions			
Particulates (unspecified)	2.05	lb	
Nitrogen Oxides	0.15	lb	
Hydrocarbons (unspecified)	0.34	lb	
Sulfur Oxides	0.36	lb	
Carbon Monoxide	22.3	lb	
CO2 (fossil)*	218	lb	
Solid Wastes			
Landfilled	2.19	lb	
Waterborne Wastes			
Suspended Solids	0.030	lb	
Oil	0.010	lb	

*Carbon dioxide released from raw material inputs to the furnace.

Source: Franklin Associates, A Division of ERG

References: C-31 and C-33.

External Scrap Procurement

The recycling of metallic scrap as feed for steel furnaces has long been an economically viable means of utilizing ferrous waste materials. Much of the scrap recovered is generated within the mills themselves; thus, the energy requirements and emissions associated with their recovery are included with normal iron and steel mill operations. However, substantial quantities of scrap are transported to iron and steel mills from external sources (including other mills at different sites).

In general, most metallic scrap undergoes similar processing prior to consumption. It is usually manually or semi-manually handled to remove valuables (e.g., tin plating, copper wire, chrome, etc.), and some contaminants (e.g., chemical impurities, organic materials). Subsequent processing includes flattening, shredding, magnetic separation, and all necessary transportation steps, including transport from the flattener to the shredder and the transport of steel scrap from the shredder to the furnace. Data for processing and transport of steel scrap is shown in Table C-40.

Table C-40

DATA FOR THE PROCUREMENT OF
1,000 POUNDS OF EXTERNAL STEEL SCRAP

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	84.4	kwh	898
Gasoline	0.30	gal	42.7
Total Process			941
Transportation Energy			
Combination truck	340	ton-miles	
Diesel	3.57	gal	567
Rail	730	ton-miles	
Diesel	1.81	gal	287
Total Transportation			854
Environmental Emissions			
Waterborne Wastes			
Suspended Solids	0.010	lb	

Source: Franklin Associates, A Division of ERG

References: C-63 and C-160.

Pig Iron Production

Iron-bearing material, coke, and fluxes are charged into a blast furnace, where the iron ore is reduced to pig iron. A blast of heated air, and, in most instances, a gaseous, liquid or powdered fuel are introduced into the furnace through openings at the bottom of the furnace shaft. The heated air burns the injected fuel and most of the coke charged in from the top to produce the heat required by the process and to provide reducing gas (carbon monoxide) that removes oxygen from the iron ore. The reduced iron melts and runs down to the bottom of the hearth. The flux combines with the impurities in the ore to produce a slag which also melts and accumulates on top of the liquid iron in the hearth (Reference C-37).

The following assumptions were made while analyzing available data for the production of pig iron from a blast furnace:

- The iron-bearing agglomerate burden for the blast furnace is assumed to be input as 60 percent iron ore pellets and 40 percent sinter (Reference C-37).
- Coproduct credit is given on a weight basis for coke breeze (very fine particles of coke) and flue dust recovered during operation of the blast furnace. Both of the materials are raw materials for sinter production. Therefore, the outputs from the blast furnace include the production of coke breeze and flue dust that are used for sinter production.
- Coke oven gas is used as a fuel at a rate of 5.63 pounds of gas per 1,000 pounds of pig iron. A density of 0.725 lb per cubic yard is assumed for the gas (Reference C-38).
- Blast furnace gas produced in the process is assumed to be used to heat air injected back into the furnace.
- About 214 pounds of blast furnace slag are produced for every 1,000 pounds of pig iron. Approximately 75 percent of the blast furnace slag produced in the United States is used in aggregate applications such as fill, road bases and the coarse aggregate components of asphalt and concrete (Reference C-40). This slag is not considered to be solid waste; however, no coproduct credit is given for the material. The remaining 25 percent of the slag is stockpiled (Reference C-40). This slag (approximately 54 lb) is considered solid waste in this analysis.
- Carbon dioxide emissions from the oxidation of coke are calculated assuming pig iron will have a carbon content of about 4.5 percent (Reference C-37) and the remaining carbon will be oxidized to carbon monoxide and carbon dioxide. It is assumed that carbon monoxide in the blast furnace gas that is not released as a fugitive emission will be oxidized to carbon dioxide when the blast gas is burned. It is further assumed that the coke has a carbon content of 88 percent (Reference C-41).

Data for production of pig iron in the blast furnace is shown in Table C-41.

Table C-41

DATA FOR THE PRODUCTION OF
1,000 POUNDS OF PIG IRON (BLAST FURNACE)

Raw Materials			
Limestone mining	48.0	lb	
Iron ore mining	58.0	lb	
Metallurgical coke production	446	lb	
Oxygen manufacture	9.30	lb	
Pellet production	832	lb	
Sinter production	554	lb	
External scrap procurement	86.0	lb	
Coke oven gas	5.60	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	10.2	kwh	109
Natural gas	728	cu ft	815
Total Process			924
Environmental Emissions			
Atmospheric Emissions			
Particulates (unspecified)	0.015	lb	
Nitrogen Oxides	0.0075	lb	
Hydrocarbons (unspecified)	0.70	lb	
Sulfur Oxides	0.75	lb	
Carbon Monoxide	9.12	lb	
Manganese compounds	1.8E-04	lb	
Lead	6.5E-06	lb	
Nickel compounds	9.7E-07	lb	
Chromium compounds	5.3E-06	lb	
Carbon dioxide, fossil*	1,279	lb	
Copper compounds	1.4E-05	lb	
Zinc compounds	4.2E-05	lb	
Solid Wastes			
Landfilled	74.3	lb	
Waterborne Wastes			
Acid (unspecified)	2.0E-04	lb	
Suspended Solids	2.0E-04	lb	
Phenol	1.0E-06	lb	
Cyanide	1.4E-06	lb	
Lead	9.1E-07	lb	
Zinc	1.4E-06	lb	
Ammonia	0.0017	lb	

*Carbon dioxide released from oxidation of coke and coke oven gas.

Source: Franklin Associates, A Division of ERG

References: C-31, C-33, C-40, C-166, and C-169.

Basic Oxygen Process Furnace (BOF)

Since the mid 1970s, the basic oxygen process has seen widespread use in steel making. In the oxygen steelmaking process, high-purity oxygen is blown under pressure through, onto or over a bath containing hot metal, steel scrap, and fluxes to produce steel (Reference C-37).

The BOF offers the advantage of using both virgin pig iron and scrap or recycled steel as feedstock. Hot metal composition and temperature are the most important variables that determine the percentage of scrap that can be charged to a heat. Typically, most pneumatic furnaces (of which the BOF is an outgrowth) consume 20 to 35 percent of the total metallic charge as external, or "cold", scrap (Reference C-37). On average, about 28.5 percent of the total metallic material charged to BOFs in the United States is cold scrap (Reference C-39).

The primary sources of heat for oxygen steelmaking processes are from the hot metal charged to the furnace and from the oxidation of carbon, silicon, manganese, phosphorus, iron and other elements contained in the hot metal charge (Reference C-37). Minimal quantities of natural gas and coke oven gas are used to supply supplemental heat to the furnace and to preheat ladles and casters.

The following assumptions were made in analyzing available data for the production of raw steel from the basic oxygen furnace:

- Coke oven gas is used as a fuel at a rate of 1.23 pounds of gas per 1,000 pounds of raw steel. A density of 0.027 lb per cubic foot is assumed for the gas (Reference C-38).
- Energy requirements and environmental emissions for heating and operating ladles and casters are included with those for the BOF.
- Coproduct credit is given on a weight basis for the slag produced in the BOF. This material is used as an input to sinter production and directly into the blast furnace for its iron content. Because the coproduct credit is given on a weight basis, the output from the BOF is increased to account for the input of BOF slag into sinter production and the blast furnace.
- Carbon dioxide emissions from the oxidation of carbon in the pig iron are calculated assuming the pig iron enters the BOF with a carbon content of about 4.5 percent (Reference C-42) and the raw steel leaving the BOF has a carbon content of about 0.75 percent. It is also assumed that all of the carbon is oxidized to carbon dioxide.

Data for production of steel in the basic oxygen furnace are presented in Table C-42.

Table C-42

DATA FOR THE PRODUCTION OF
1,000 POUNDS OF STEEL IN BASIC OXYGEN FURNACE (BOF)

			Total Energy Thousand Btu
Raw Materials			
Limestone mining	8.20	lb	
Lime production	20.0	lb	
Iron ore mining	8.90	lb	
Oxygen manufacture	72.0	lb	
External scrap procurement	245	lb	
Pig iron production (blast furnace)	759	lb	
Energy Usage			
Process Energy			
Electricity (grid)	126	kwh	1,340
Total Process			1,340
Transportation Energy			
Combination truck	250	ton-miles	
Diesel	3	gal	417
Environmental Emissions			
Atmospheric Emissions			
Particulates (unspecified)	0.11	lb	
Nitrogen Oxides	0.052	lb	
Hydrocarbons (unspecified)	0.0018	lb	
Sulfur Oxides	0.016	lb	
Carbon Monoxide	0.84	lb	
Lead	5.1E-06	lb	
Nickel compounds	8.8E-07	lb	
Chromium compounds	1.9E-06	lb	
Carbon dioxide, fossil*	125	lb	
Copper compounds	8.8E-07	lb	
Zinc compounds	7.4E-05	lb	
Solid Wastes			
Landfilled	70.2	lb	
Waterborne Wastes			
Suspended Solids	5.9E-04	lb	
Oil	4.9E-05	lb	
Lead	1.5E-06	lb	
Zinc	3.7E-05	lb	

*Carbon dioxide released from oxidation of carbon in the pig iron.

Source: Franklin Associates, A Division of ERG

References: C-31, C-33, C-166, C-169, and C-177.

CORRUGATED PAPERBOARD

The production of corrugated products includes:

- Unbleached Kraft Linerboard Production
- Semichemical Medium Production
- Old Corrugated Container (OCC) Collection
- Recycled Paperboard (Linerboard and Medium) Production
- Corrugated Tray Fabrication

The material flows for the production of corrugated containers are shown in Figure C-9. Details on the unit processes for corrugated paperboard production are provided below.

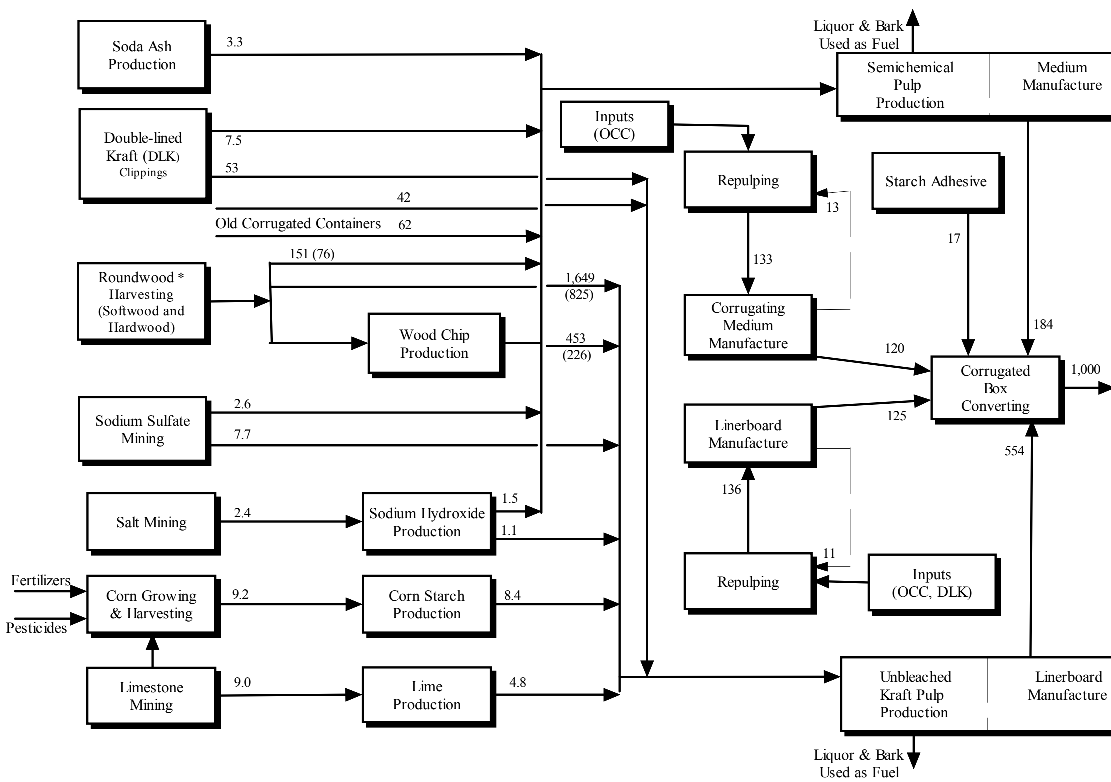

Figure C-9: Flow diagram for corrugated paperboard production

Unbleached Kraft Linerboard Production

Unbleached kraft paperboard is the main material used for folding boxes and corrugated linerboard. The production of unbleached kraft paperboard includes the following unit processes:

- Roundwood Harvesting
- Wood Residues
- Limestone Mining
- Lime Production
- Salt Mining
- Sodium Hydroxide Production
- Sodium Sulfate Mining and Processing
- Sulfur Production
- Sulfuric Acid Production
- Nitrogen Fertilizer
- Phosphate Fertilizer
- Potash Fertilizer
- Corn Growing and Harvesting
- Corn Starch
- Unbleached Kraft Paperboard Production

The material flows for unbleached kraft paper/paperboard are shown in Figure C-10.

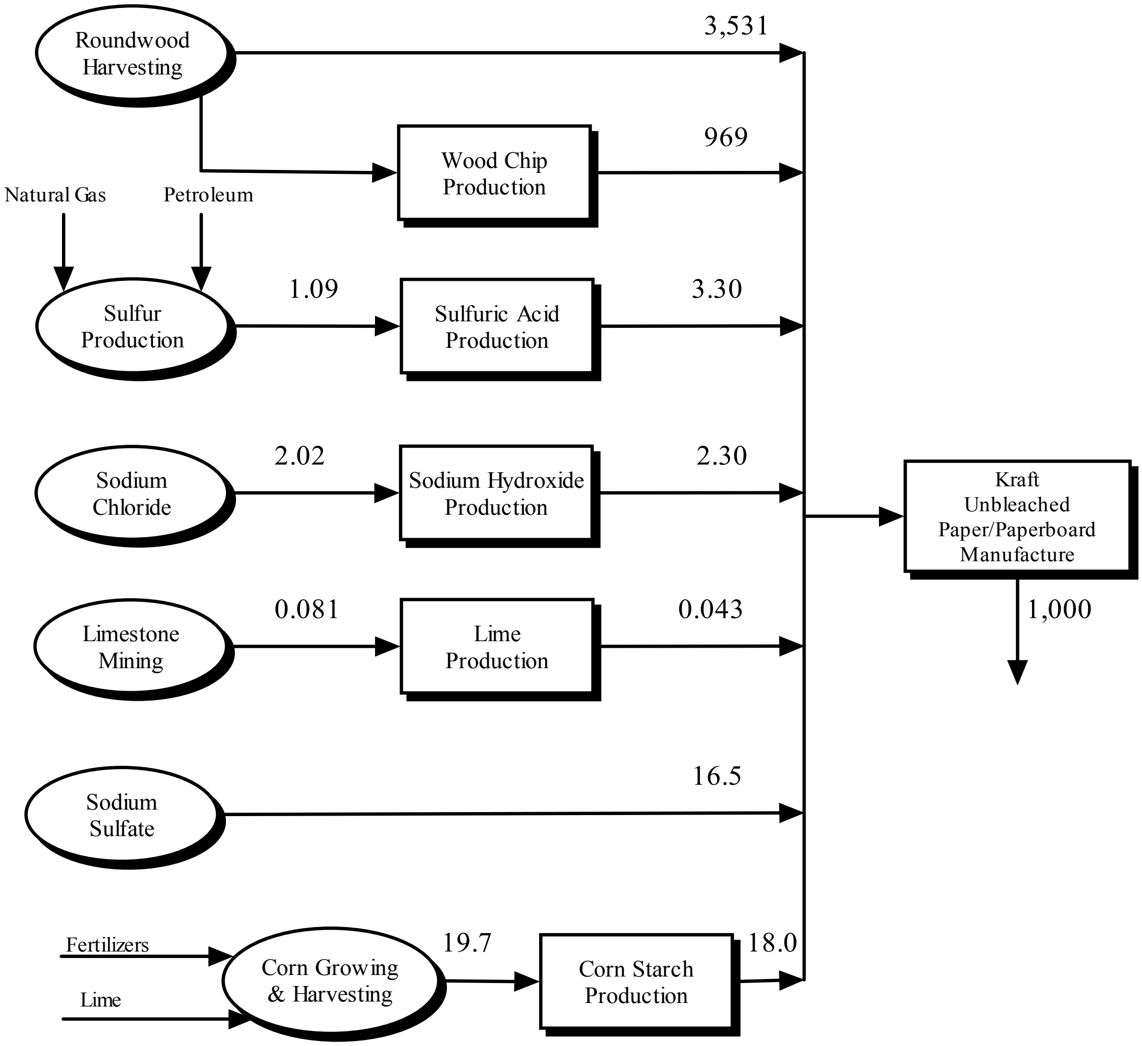

Figure C-10: Flow diagram for unbleached paperboard production

Discussions and data for the unit processes of limestone mining, lime production, salt mining, and sodium hydroxide production are provided earlier in this appendix and are not repeated in this section. The unit processes of roundwood harvesting, wood residues, sodium sulfate mining and processing, sulfur production, sulfuric acid production, fertilizer production (including nitrogen, phosphate, and potash fertilizers), corn growing and harvesting, corn starch production, and unbleached kraft paperboard production are discussed below.

Roundwood Harvesting

The technique of harvesting trees has become a highly mechanized process. Typically, trees are harvested by using a feller buncher to fell the wood. The wood is pulled to a landing or processing area, where branches are removed and the wood is cut to manageable lengths for loading on trucks and delivery to the mill. After the wood is cleared from the forest, a variety of site preparations are used. On some sites debris is manually removed from the forest before replanting, while other sites are left to grow back naturally. Finally, some harvested sites are burned to remove any remaining debris before replanting. Emissions do result from clearing the site by burning, but this practice occurs infrequently compared to the mass of trees harvested. It is assumed for this study that these emissions are negligible.

Trees harvested specifically for wood pulp production account for approximately 37 percent of the wood delivered to the paper mill in this dataset (Reference C-172). The remainder comes from wood residues (sawdust and chips) generated by lumber production or other wood processing operations, described in the following section.

An unknown amount of water pollution in the form of suspended solids results from runoff from road building into the harvested forests. However, at present, it is not possible to estimate accurately to what extent these solids are generated. Their final deposition is probably at other locations within the forest, and not in streams. Therefore, this category was not included because the amount of stream pollution from this source is quite likely very small and could not be determined from published or unpublished sources.

Data for roundwood harvesting is shown in Table C-43.

Table C-43

**DATA FOR THE HARVESTING
OF 1,000 POUNDS OF ROUNDWOOD**

Energy Usage		**Total Energy Thousand Btu**
Process Energy		
Diesel	0.32 gal	50.8
Total Process		50.8
Transportation Energy		
Combination Truck	33.0 ton-miles	
Diesel	0.35 gal	55.0
Total Transportation		55.0

References: C-46

Source: Franklin Associates, A Division of ERG

Wood Residues

Wood residues used in production of paper are either mill residues generated by lumber mills or other wood processing operations, or forest residues. It is estimated that mill residues make up about 90 percent of the wood residues used by paper mills, and forest residues make up the remaining 10 percent. Data for the production of wood residues are shown in Table C-44.

Typically the wood that a sawmill receives will already be delimbed and cut to manageable lengths. The roundwood is sorted by diameter and then sent to a debarker. After debarking, the logs are conveyed through a series of cutting and planing operations. Roughly 75 to 80 weight percent of the tree as received is converted to lumber, with the remaining 20 to 25 percent becoming wood chips and fines. The environmental burdens for the outputs of these processes are allocated to the coproducts on a mass basis. The chips are sold to pulp mills, and the fines are either burned as an energy source or burned for waste disposal.

Forest residues are small diameter trees, limbs and cuttings, which are turned into chips in the forest. A flail-chipper is used to produce pulp-quality chips from tree-length limbs (Reference C-157). In general, wood residues are generated on site or quite close to the mills.

Table C-44

DATA FOR THE PRODUCTION OF
1,000 POUNDS OF WOOD RESIDUES

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	11.0	kwh	117
Diesel	0.025	gal	3.97
Total Process			121
Transportation Energy			
Combination Truck	17.0	ton-miles	
Diesel	0.18	gal	28.3
Total Transportation			28.3
Environmental Emissions			
Solid Wastes			
Landfilled	1.70	lb	

References: C-46

Source: Franklin Associates, A Division of ERG

Sodium Sulfate Mining and Processing

Sodium sulfate is consumed in the Kraft pulping process. The upper levels of Searles Lake, California, the Great Salt Lake in Utah, and the brines of west Texas all contain sodium sulfate; however, only two plants in Texas and California were operating in 2006 (Reference C-158). Typically sodium sulfate crystals are removed from cold brine. The crystals are then dissolved again and precipitated to achieve the desired purity. Data for the production of sodium sulfate are shown in Table C-45.

Table C-45

DATA FOR THE PRODUCTION OF
1,000 POUNDS OF SODIUM SULFATE

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	38.7	kwh	412
Natural Gas	741	cu ft	830
Coal	101	lb	1,130
Gasoline	0.0088	gal	1.25
Total Process			2,373
Transportation Energy			
Rail	400	ton-miles	
Diesel	0.99	gal	158
Total Transportation			158
Environmental Emissions			
Atmospheric Emissions			
Particulates (unspecified)	0.39	lb	
Solid Wastes			
Landfilled	60.0	lb	
Waterborne Wastes			

References: C-158

Source: Franklin Associates, A Division of ERG

Sulfur Production

Sulfur exists in nature as elemental sulfur and is also found in ores such as pyrite (FeS_2). Sulfur is also recovered from hydrogen sulfide (H_2S), a component of petroleum and natural gas. The Frasch process (sulfur obtained from limestone) is no longer used in the United States (Reference C-159). The U.S. now produces its sulfur using the Claus process (from natural gas and petroleum). A description of the Claus sulfur production process follows. Sulfur production data are shown in Table C-46.

Recovery of sulfur from sour natural gas and crude oil via the Claus process accounts for the total amount of the sulfur produced in the United States. Approximately 79 percent of the sulfur produced via Claus recovery is obtained from hydrogen sulfide recovered from petroleum refining, and the remaining 21 percent is recovered from natural gas sweetening (Reference C-159). The following data includes data for the production of sulfur from petroleum refining only.

Hydrogen sulfide is recovered from refinery gases by absorption in a solvent or by regenerative chemical absorption (Reference C-65). Hydrogen sulfide concentrations in the gas from the absorption unit vary. For this analysis, an industry average H_2S gas concentration of 85 percent is used (References C-46 and C-65). This concentrated hydrogen sulfide stream is treated by the Claus process to recover the sulfur. The Claus process is based upon the reaction of hydrogen sulfide with sulfur dioxide according to the exothermic reaction (Reference C-65):

$$2H_2S + SO_2 \rightarrow 3S + 2H_2O \qquad \text{(Reaction 1)}$$

Sulfur dioxide for the reaction is prepared by oxidation of hydrogen sulfide with air or oxygen in a furnace using either the partial combustion process (once-through process) or the split-stream process. The partial combustion method is used when the H_2S concentration is greater than 50 percent and the hydrocarbon concentration is less than 2 percent. The split stream process is used when there is an H_2S concentration of 20 to 50 percent and a hydrocarbon concentration of less than 5 percent.

In the partial combustion method, the hydrogen sulfide-rich gas stream is burned with a fuel gas in an oxygen-limited environment to oxidize one-third of the H_2S to SO_2 according to the reaction (Reference C-160):

$$2H_2S + 2O_2 \rightarrow SO_2 + S + 2H_2O \qquad \text{(Reaction 2)}$$

Sulfur is removed from the burner and the H_2S/SO_2 mixture moves to the catalytic converter chambers.

In the split stream process, one-third of the hydrogen sulfide is split off and completely oxidized to SO_2 according to the reaction:

$$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O \qquad \text{(Reaction 3)}$$

The remaining two-thirds of the H_2S is mixed with the combustion product and enters the catalytic converter chambers.

The H_2S and SO_2 mixture from either process is passed through one or more catalyst beds and is converted to sulfur, which is removed by condensers between each bed (Reference 13). For this analysis, an H_2S concentration of 85 percent has been assumed; therefore, it is also assumed that the partial combustion process is used.

Although efficiencies of 96 to 99 percent sulfur recovery have been demonstrated for the Claus process, recovery is usually not over 96 percent and is limited by thermodynamic considerations (References C-65 and C-160). For this analysis, a sulfur recovery efficiency of 95 percent is assumed.

The energy generated from burning hydrogen sulfide to produce SO_2 is usually recovered and used directly to reheat the process stream in secondary and tertiary condensers, or recovered as steam for use in other processes (Reference C-160). Heat released from cooling the exothermic reaction to form sulfur is also recovered.

Table C-46

DATA FOR THE MINING AND PRODUCTION OF 1,000 POUNDS OF SULFUR

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	140	kwh	1,489
Natural Gas	2,163	cu ft	2,423
LPG	0.14	gal	15.1
Distillate Oil	0.20	gal	31.8
Residual Oil	3.39	gal	582
Gasoline	0.086	gal	12.2
Total Process			4,553
Transportation Energy			
Combination Truck	24.2	ton-miles	
Diesel	0.25	gal	40.4
Rail	1.33	ton-miles	
Diesel	0.0033	gal	0.52
Barge	74.0	ton-miles	
Diesel	0.059	gal	9.40
Residual Oil	0.20	gal	33.8
Ocean Freighter	1,521	ton-miles	
Diesel	0.29	gal	45.9
Residual	2.60	gal	446
Pipeline-Natural Gas	133	ton-miles	
Natural Gas	91.8	cu ft	103
Pipeline-Petroleum Products	203	ton-miles	
Electricity	4.43	kwh	45.3
Total Transportation			724

Environmental Emissions

Atmospheric Emissions		
Aldehydes (unspecified)	0.086	lb
Ammonia	0.0026	lb
Chlorine	1.0E-04	lb
HCl	7.6E-05	lb
Hydrocarbons (unspecified)	16.1	lb
Lead	7.1E-07	lb
Particulates (unspecified)	2.53	lb
Sulfur Oxides	0.86	lb
Solid Wastes		
Landfilled	53.2	lb
Waterborne Wastes		
Acid (unspecified)	5.6E-07	lb
Ammonia	9.0E-04	lb
BOD	0.0069	lb
Chromium (unspecified)	2.2E-06	lb
COD	0.033	lb
Dissolved Solids	0.47	lb
Iron	2.1E-04	lb
Lead	1.0E-06	lb
Metal Ion (unspecified)	0.012	lb
Oil	0.030	lb
Phenol/Phenolics	3.9E-05	lb
Suspended Solids	0.0063	lb
Zinc	1.5E-05	lb

References: C-43, C-69, and C-95.

Source: Franklin Associates, A Division of ERG

Sulfuric Acid Production

All sulfuric acid produced in the U.S. is produced by the contact process (Reference C-161). The sulfur input streams used by contact plants can be of three different forms: (1) elemental sulfur, (2) spent sulfuric acid or hydrogen sulfides, and (3) metal sulfide ores or smelter gas. Contact plants that use elemental sulfur account for 81 percent of sulfuric acid production (Reference C-161).

There are three basic steps in the contact process. The first step oxidizes (burns) sulfur to sulfur dioxide (SO_2). The second step catalytically oxidizes sulfur dioxide to sulfur trioxide (SO_3). The third step dissolves the sulfur trioxide into a 98 percent solution of sulfuric acid. The third step can also produce sulfuric acid by adding sulfur trioxide directly to water. However, when sulfur trioxide is added directly to water, the reaction is slow and tends to form a mist.

During sulfuric acid production, the burning of sulfur produces heat, which in turn is used to generate steam. This steam is usually used in adjacent processing plants and supplies energy to the sulfuric acid plant.

Process data for sulfuric acid production are shown in Table C-47.

Table C-47

DATA FOR THE PRODUCTION OF
1,000 POUNDS OF SULFURIC ACID

			Total Energy Thousand Btu
Raw Materials			
Sulfur Mining and Production	329	lb	
Energy Usage			
Process Energy			
Electricity	12.0	kwh	128
Total Process			128
Transportation Energy			
Combination Truck	13.0	ton-miles	
Diesel	0.14	gal	21.7
Rail	55.0	ton-miles	
Diesel	0.14	gal	21.7
Barge	55.0	ton-miles	
Diesel	0.044	gal	6.99
Residual Oil	0.15	gal	25.1
Total Transportation			75.4
Environmental Emissions			
Atmospheric Emissions			
CO_2 (fossil)	4.05	lb	
Particulates (unspecified)	1.10	lb	
Sulfur Oxides	13.0	lb	
Solid Wastes			
Landfilled	3.50	lb	
Waterborne Wastes			
Acid (unspecified)	7.00	lb	
BOD	0.20	lb	
Suspended Solids	0.60	lb	

References: C-96

Source: Franklin Associates, A Division of ERG

Fertilizers

The following sections discuss the production of fertilizers used in corn production. Because of the many unit processes required to produce individual fertilizers that are used at a rate of less than 20 pounds per 1,000 pounds of corn, the cradle-to-fertilizer results for each type of fertilizer are summarized in an aggregated table at the end of each section.

Nitrogen Fertilizer Production. Nitrogen as a single nutrient is commonly applied in the form of anhydrous ammonia. The United States imports more than half of its nitrogen fertilizer, mostly from Canada, Russia, and Trinidad & Tobago (Reference C-162). The steps in the production of nitrogen fertilizer are listed below.

- Natural Gas Production
- Natural Gas Processing
- Production of Nitrogen Fertilizer as Ammonia

Natural gas production and natural gas processing are discussed previously in this appendix and are not repeated in this section. Nitrogen fertilizer is applied in the form of anhydrous ammonia, which is 82 percent by weight nitrogen. Ammonia production is discussed in the following section.

Production of Nitrogen Fertilizer as Ammonia. Ammonia is produced primarily by steam reforming natural gas. Natural gas is fed with steam into a tubular furnace where the reaction over a nickel reforming catalyst produces hydrogen and carbon oxides. The primary reformer products are then mixed with preheated air and reacted in a secondary reformer to produce the nitrogen needed in ammonia synthesis. The gas is then cooled to a lower temperature and subjected to the water shift reaction in which carbon monoxide and steam are reacted to form carbon dioxide and hydrogen. The carbon dioxide is removed from the shifted gas in an absorbent solution. Hydrogen and nitrogen are reacted in a synthesis converter to form ammonia (Reference C-65).

The energy data for ammonia was calculated from secondary sources (Reference C-65) and from stoichiometry. The atmospheric emissions and solid wastes are estimates, while the waterborne emissions are from a 1970’s source (Reference C-163), although these emissions were reviewed and revised in 1994. Aggregated data for nitrogen fertilizer production are shown in Table C-48.

Table C-48

**DATA FOR THE PRODUCTION
OF 1,000 POUNDS OF NITROGEN FERTILIZER (AMMONIA)**

			Total Energy Thousand Btu
Raw Materials			
Processed Natural Gas*	267	lb	
Energy Usage			
Process Energy			
Electricity (grid)	63.5	kwh	653
Natural gas	2,239	cu ft	2,508
Total Process			3,161
Transportation Energy			
Rail	125	ton-miles	
Diesel	0.31	gal	49.2
Pipeline-petroleum products	1.25	ton-miles	
Electricity	0.027	kwh	0.28
Total Transportation			49.5
Environmental Emissions			
Atmospheric Emissions			
Ammonia	1.00	lb	
Other Organics	1.00	lb	
Fossil Carbon Dioxide**	97.0	lb	
Solid Wastes			
Landfilled	0.20	lb	
Waterborne Wastes			
Ammonia	0.060	lb	
BOD	0.050	lb	
COD	0.23	lb	
Oil	0.050	lb	
Suspended solids	0.050	lb	

*The nitrogen inputs to ammonia production are also produced (from air) during the steam reforming process sequence.
** Carbon dioxide produced from reforming reactions.

References: J-2 through J-5

Source: Franklin Associates, A Division of ERG

Phosphate Fertilizer Production. Phosphate fertilizer applied as a single nutrient is most commonly in the form of superphosphate, with 16 to 20 percent available P_2O_5, or triple superphosphate, with 44 to 51 percent available P_2O_5. Superphosphates are produced by the action of sulfuric acid on phosphate rock, while triple superphosphates are made by adding phosphoric acid to phosphate rock (References C-52 and C-164). The data are based on half of the phosphate applied as superphosphate and half as triple superphosphate. The following process steps are required for the manufacture of the phosphate fertilizers:

- Superphosphate
  - Phosphate Rock Mining
  - Crude Oil Production
  - Crude Oil Refining
  - Natural Gas Production
  - Natural Gas Processing
  - Sulfur Production
  - Sulfuric Acid Production
  - Superphosphate Production
- Triple Superphosphate
  - Phosphate Rock Mining
  - Silica Mining and Processing
  - Coal Mining
  - Metallurgical Coke Production
  - Elemental Phosphorus Production
  - Oxygen Production
  - Phosphorus Pentoxide Production
  - Phosphoric Acid Production
  - Triple Superphosphate Production
- Phosphate Fertilizer Production

Superphosphate Production. Superphosphate is produced by the addition of sulfuric acid to phosphate rock. This superphosphate is a mixture of gypsum and calcium phosphate.

Triple Superphosphate Production. Triple superphosphate is produced by the addition of phosphoric acid to phosphate rock. It has three times the amount of available phosphate as in superphosphate and contains no gypsum.

During the production of elemental phosphorus, metallurgical coke is used as a raw material. As a byproduct of its reaction with silica, heat is created and used as an energy source for the reaction.

Phosphate Fertilizer Production. Phosphate fertilizer is applied in the form P_2O_5. The superphosphate is applied with 20 percent available P_2O_5 and the triple superphosphate with 50 percent available P_2O_5.

Aggregated data for all steps in the production of phosphate fertilizer are shown in Table C-49.

Table C-49

DATA FOR THE PRODUCTION OF
1,000 POUNDS OF PHOSPHATE FERTILIZER
(includes mining of phosphate rock and all processing steps
for converting listed raw materials into fertilizer)

Raw Materials			
Phosphate rock mining	4,685	lb	
Sulfur prod	749	lb	
Silica mining & proc	2,271	lb	
Coal mining	2,500	lb	
Oxygen	540	lb	
Energy Usage			**Energy Thousand Btu**
Process Energy			
Electricity	1,378	kwh	14,662
Natural Gas	2,896	cu ft	3,244
Total Process			17,906
Transportation Energy			
Combination Truck	146.9	ton-miles	
Diesel	1.54	gal	245
Rail	241	ton-miles	
Diesel	0.60	gal	94.8
Barge	149	ton-miles	
Diesel	0.12	gal	18.87
Residual Oil	0.40	gal	67.8
Total Transportation			426
Environmental Emissions			
Atmospheric Emissions			
Particulates (unspecified)	105	lb	
Fluorine	0.0013	lb	
Solid Wastes			
Landfilled	100	lb	
Waterborne Wastes			
Suspended Solids	9.89	lb	

References: C-51, C-69, C-71, C-72, C-73, C-74 through C-83.

Source: Franklin Associates, A Division of ERG

Potash Fertilizer. Potash fertilizers are derived mainly from mined potash salts. Potash fertilizer is generally applied in the form of potassium chloride (KCl), which is sold in various agricultural grades, containing 60 to 62 percent K_2O, 48 to 52 percent K_2O, or 22 percent K_2O. The United States imports approximately 80 percent of its potash fertilizer, mostly from Canada (Reference 20).

The potash fertilizer analyzed in this study is based on application as KCl containing 50 percent K_2O. The aggregated process data shown in Table C-50 are based on an estimated 75 percent of KCl produced from sylvinite and 25 percent from brine extraction.

Table C-50

DATA FOR THE PRODUCTION OF
1,000 POUNDS OF POTASH FERTILIZER
(includes all process steps from raw material extraction through fertilizer production)

			Energy Thousand Btu
Raw Materials			
Sylvinite and brines	1,883	lb	
Energy Usage			
Process Energy			
Electricity	18.8	kwh	200
Natural Gas	6,697	cu ft	7,501
Coal	121	lb	1,359
Residual Oil	3.45	gal	592
Total Process			9,651
Transportation Energy			
Combination Truck	50.0	ton-miles	
Diesel	0.53	gal	83.4
Rail	791	ton-miles	
Diesel	1.96	gal	312
Total Transportation			395
Environmental Emissions			
Atmospheric Emissions			
Particulates (unspecified)	9.59	lb	
Solid Wastes			
Landfilled	113	lb	

Source: Franklin Associates, A Division of ERG

References: C-48, C-51, C-52, C-72 through C-75, C-77, and C-81.

Corn Growing and Harvesting

Whole grain corn is composed of 71.7 percent starch (Reference C-53). Corn is a warm weather plant requiring a growing season of about 140 days with an average daytime temperature of 75°F with nighttime temperatures exceeding 58°F. Irrigation is used on most corn-growing farms to supplement inadequate rainfall. Other inputs to corn growing modeled in this analysis include fertilizer and lime, which are added to bring necessary nutrients to the soil. Pesticides are added to destroy insects, fungus, and any other pest that would hurt the plant; however, pesticide production and runoff emissions are not included in this model for several reasons, including lack of data on production of individual pesticides as well as regional variations in the types and quantities of pesticides used, and variations in pesticide runoff due to differences in land geographies and local rainfall.

Today, corn harvesting is mostly done by multi-row combines. The corn is then stored for drying. The data shown in Table C-51 include transport to a wet milling plant.

Table C-51

DATA FOR THE GROWING AND HARVESTING OF 1,000 POUNDS OF CORN

Raw Materials			
Nitrogen fertilizer	18.5	lb	
Potash fertilizer	8.50	lb	
Phosphate fertilizer	6.90	lb	
Lime	2.20	lb	
Energy Usage			**Energy Thousand Btu**
Process Energy			
Natural Gas	96.9	cu ft	109
Diesel	0.63	gal	100
Total Process			209
Transportation Energy			
Combination Truck	25.0	ton-miles	
Diesel	0.26	gal	41.7
Rail	350	ton-miles	
Diesel	0.87	gal	138
Total Transportation			180
Environmental Emissions			
Waterborne Wastes			
Nitrogen	1.18	lb	
Phosphates	0.27	lb	

Reference: C-173.

Source: Franklin Associates, A Division of ERG

Corn Starch Production

Corn starch is produced from corn by wet milling. The corn is soaked in steeping tanks containing a solution of 0.3 percent sulfur dioxide in water to soften the kernel and dissolve inorganic components. This steep liquor is later concentrated for sale as a coproduct. The softened corn is lightly milled to free the germ from the kernel. The germ is then processed for oil removal. The remaining corn fraction, mostly starch, protein, and hulls, is then heavily milled. The starch is washed from the hulls, and the resulting starch slurry is separated, refined, washed, and dried. Process data for production of corn starch are shown in Table C-52.

Starch is a surface sizing material that fills in surface voids and therefore reduces the rate of liquid penetration in dry paper (Reference C-165).

Table C-52

DATA FOR THE PRODUCTION OF
1,000 POUNDS OF CORN STARCH

Raw Materials			
Corn Growing	1,088	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	13.5	kwh	144
Natural Gas	485	cu ft	543
Coal	15.6	lb	175
Residual Oil	0.70	gal	120
Total Process			982
Transportation Energy			
Combination Truck	400	ton-miles	
Diesel	4.20	gal	667
Total Transportation			667
Environmental Emissions			
Atmospheric Emissions			
CO2 (non-fossil)	0.33	lb	
Nitrogen Oxides	3.6E-05	lb	
Particulates (unspecified)	0.069	lb	
Sulfur Oxides	0.58	lb	
Waterborne Wastes			
BOD	1.22	lb	
COD	1.95	lb	
Dissolved Solids	3.33	lb	
Suspended Solids	0.16	lb	

References: C-56, C-84

Source: Franklin Associates, A Division of ERG

Virgin Unbleached Kraft Paperboard Production

Kraft pulp is the most widely used type of wood pulp in the United States today, accounting for approximately 80 percent of the total wood pulp produced (Reference C-166).

The kraft pulping process is based on chemical digestion of wood which has been previously debarked and chipped. The digester is a closed container that holds the wood chips and digestion liquors. The liquor is mainly an aqueous solution of chemicals including sodium sulfide and sodium hydroxide.

In order for digestion to take place, heat and pressure are applied to the mixture of wood and liquor. The digestion process delignifies the wood and removes other chemical components from the wood, leaving mostly wood fiber with some lignin and complex sugars.

One of the features of the kraft process is that the used digestion liquor, called black liquor, is burned for energy. Because the liquor contains a high percentage of flammable wood components, it burns readily. The remaining digestion chemicals, called green liquor, are removed and reacted with quicklime. The resulting white liquor containing sodium hydroxide and sodium sulfide is returned to the digester.

Combustion of black liquor and the bark removed from logs entering the mill often provides sufficient energy to operate a pulp mill (Reference C-165). The black liquor that is burned in the recovery furnace is treated as fuel for the process.

After the wood pulp is “blown” from the digester by the steam used in the process, the pulp is washed free of the chemicals, screened, and refined for entry into the paper-forming section of the mill.

The fiber is pumped to the paper machine as a very dilute suspension in water. To form the paperboard, the fiber suspension drains onto a finely woven plastic or wire mesh belt which moves over a series of vacuum boxes where the sheet is mechanically dewatered. Next, the sheet is transferred from the wire mesh to a synthetic fabric. This felt conveys the sheet to a pressure roll with an internal vacuum box designed to remove additional water. This same pressure roll also transfers the web to the dryer. This operation is the final drying operation for the sheet. The paper and paperboard (containing about five percent moisture) is then wound onto rolls.

Process data for unbleached kraft paperboard production are presented in Table C-53.

Table C-53

**DATA FOR THE PRODUCTION
OF 1,000 POUNDS OF UNBLEACHED PAPERBOARD**

			Total Energy Thousand Btu
Raw Materials			
Roundwood	3,531	lb	
Wood chips	969	lb	
Sodium sulfate	16.5	lb	
Sodium hydroxide	2.30	lb	
Lime	10.3	lb	
Corn starch	18.0	lb	
Energy Usage			
Process Energy			
Electricity (grid)	85.1	kwh	876
Natural gas	1,163	cu ft	1,303
LPG	0.0013	gal	0.14
Coal	271	lb	3,043
Residual oil	0.55	gal	94.4
Wood	9.39	Mil. Btu	9,388
Total Process			14,704
Transportation Energy			
Combination truck	390	ton-miles	
Diesel	4.10	gal	650
Rail	142	ton-miles	
Diesel	0.35	gal	55.9
Total Transportation			706
Environmental Emissions			
Atmospheric Emissions			
Carbon monoxide	8.22	lb	
Aldehydes	0.012	lb	
Nitrogen oxides	7.05	lb	
Particulates	1.62	lb	
Sulfur oxides	11.9	lb	
Ammonia	0.091	lb	
Mercury	1.0E-04	lb	
Total reduced sulfur	0.058	lb	
Solid Wastes	71.9	lb	
Waterborne Wastes			
BOD	1.29	lb	
COD	13.0	lb	
Suspended solids	1.76	lb	
Ammonia	0.043	lb	
Phosphates	0.090	lb	
Phosphorus	0.065	lb	
Nitrates	0.0024	lb	
Aluminum	0.11	lb	

References: C-88

Source: Franklin Associates, A Division of ERG

Semichemical Medium

Semichemical medium forms the inner layer of corrugated paperboard. The production of virgin semichemical medium includes the following steps:

- Roundwood Harvesting
- Salt Mining
- Caustic Soda Production
- Soda Ash Production
- Sodium Sulfate Mining
- Semichemical Medium Production

Roundwood harvesting, salt mining, caustic soda production, soda ash production, and sodium sulfate mining are discussed previously in this appendix and thus are not repeated here. The production of semichemical medium is discussed below.

Most of the increase in semichemical pulp production in the past 40 years has been made using non-sulfur semichemical processes, not only because of tightened environmental regulations, but also because of realization of higher yields and simpler recovery systems. There are three major pulping processes used to manufacture semichemical pulps in integrated as well as stand-alone semichemical pulp mills:

- Neutral Sulfite (NSSC) process, which uses sodium carbonate and sulfur or, in some cases, sodium sulfite purchased as a byproduct from a nearby chemical operation as the cooking chemical.
- Green Liquor process, which uses green liquor for the kraft recovery process as the cooking chemical.
- Non-sulfur process, which uses a combination of sodium carbonate, sodium hydroxide, and traces of other proprietary chemicals to enhance the properties of the pulp.

Many semichemical operations integrated with kraft mills use green liquor from the kraft recovery process as the cooking chemical. This allows integration of the semichemical cooking chemical preparation and recovery into the kraft recovery cycle. The quality of semichemical pulp is superior when produced by the neutral sulfite process, but it produces less pulp per pound of wood. The pulp yields from wood in the semichemical pulping processes range from 75 to 88 percent.

The data presented is based on two different process – the non-sulfur process and the NSSC process. A market share average of 60 percent non-sulfur and 40 percent NSSC was used in combining the data sets (Reference C-103).

Semichemical paperboard typically contains some recycled fiber. The proportion of recycled fiber will vary for specific mills. For this study, the fibrous raw materials used by the mills surveyed are similar to the national averages for semichemical paperboard, which include approximately 24% recycled fiber. Data for the production of 1,000 pounds of semichemical paperboard are shown in Table C-54.

Table C-54

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF SEMICHEMICAL MEDIUM

Raw Materials			
Soda Ash	18.0	lb	
Double-Lined Kraft Clippings	18.4	lb	
Old Corrugated Containers	265	lb	
Roundwood	876	lb	
Sodium Sulfate	14.2	lb	
Sodium Hydroxide	8.40	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	326	kwh	3,355
Natural gas	186	cu ft	208
Residual oil	0.14	gal	24.0
Hydropower	0.18	Mil. Btu	180
Wood	4.27	Mil. Btu	4,270
Total Process			8,037
Transportation Energy			
Combination truck	58.0	ton-miles	
Diesel	0.61	gal	96.7
Total Transportation			96.7
Environmental Emissions			
Solid Wastes	15.0	lb	
Waterborne Wastes			
BOD	3.26	lb	
COD	5.02	lb	
Suspended solids	3.72	lb	

References: C-100, C-102, C-103

Source: Franklin Associates, A Division of ERG

Old Corrugated Container (OCC) Collection

The majority of postconsumer fiber used in kraft paper is recovered from old corrugated containers (OCC). Recovered office paper and magazines contribute a small amount to the postconsumer content in recycled kraft paper. The infrastructure for recycling postconsumer corrugated shipping containers in the United States is well established, particularly for warehouses and supermarkets. Typically, the used boxes are loaded onto a conveyer that takes them to a baler. The bales of boxes are then fork-lifted into a diesel truck that ships them to the recycled paperboard mill, where they are repulped.

The resource requirements and environmental emissions data for collecting 1,000 pounds of old corrugated containers are shown in Table C-55. These data include the transport to collect the boxes and to ship the boxes to the recycled paperboard mill.

Table C-55

DATA FOR THE COLLECTION OF 1,000 POUNDS OF OLD CORRUGATED CONTAINERS (OCC)

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	0.95	kwh	9.78
Diesel	0.14	gal	22.2
Total Process			32.0
Transportation Energy			
Combination truck	80.0	ton-miles	
Diesel	0.84	gal	133
Single unit truck	10.0	ton-miles	
Diesel	0.23	gal	35.7
Total Transportation			169

References: C-102, C-104, C-105

Source: Franklin Associates, A Division of ERG

Recycled Paperboard (Linerboard and Medium) Production

Collected wastepaper mostly includes old corrugated containers (OCC) and double-lined kraft (DLK). Also, small amounts of postconsumer office wastepaper and old newspapers can be used. Typically, these products are recycled by repulping shredded material.

In the repulping process, the collected paper is mixed with water in a huge blender-like vat, called a repulper. Blades at the bottom of the vat churn the water and beat the paper fiber away from any coatings. As the repulper is drained, filters allow the paper fibers to pass through. The coating is screened off and disposed. Much of the short fibers are also screened off of the pulp. The sludge can be collected from the repulper for beneficial uses, such as animal bedding or ground cover at landfills, or can be thrown away as solid waste.

The proportion of postconsumer fiber and industrial scrap consumed varies for specific recycled paperboard mills. The fibrous raw materials used in this data set reflect the national averages. Data for the production of 1,000 pounds of recycled paper for medium or linerboard are shown in Table C-56.

Table C-56

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF RECYCLED PAPERBOARD FOR LINERBOARD OR MEDIUM

Raw Materials			
Inputs for 1,000 Pounds of Linerboard			
Postconsumer Paper (OCC)	1,014	lb	
Kraft clippings (DLK)	42.2	lb	
Inputs for 1,000 Pounds of Medium			
Postconsumer Paper (OCC)	1,056	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	291	kwh	2,995
Natural gas	531	cu ft	595
LPG	0.029	gal	3.13
Coal	220	lb	2,471
Distillate oil	0.014	gal	2.22
Residual oil	0.24	gal	41.2
Diesel	0.13	gal	20.6
Total Process			6,127
Transportation Energy			
Combination truck	75.0	ton-miles	
Diesel	0.79	gal	125
Environmental Emissions			
Solid Wastes	62.2	lb	
Waterborne Wastes			
BOD	3.03	lb	
COD	4.76	lb	
Suspended solids	3.01	lb	
Dissolved solids	0.30	lb	
Ammonia	0.0050	lb	
Phosphates	0.065	lb	
Sulfides	0.20	lb	
Oil	0.20	lb	
Phenol	0.0024	lb	
Aluminum	0.10	lb	
Iron	0.20	lb	
Zinc	0.0028	lb	

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Source: Franklin Associates, A Division of ERG

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C-168 Data compiled by Franklin Associates, Ltd., based on contact with confidential DMT sources. 1988-1992.

C-169 Data compiled by Franklin Associates, Ltd., based on contact with confidential PET sources using DMT technology. 1992-1993.

C-170 Data from the EcoInvent database and based on publicly available data provided by NatureWorks® in 2007.

C-171 Information taken from the website: http://www.gtchouston.com/technologie/otech-dmt.htm.

C-172 Based on Table 2-1 and Figure 2-2 in **Biomass Energy Consumption in the Forest Products Industry**. Final Report. March 28, 2006. Prepared for the U.S. Department of Energy, Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels by RTI International.

C-173 Shapouri et al. **The Energy Balance of Corn Ethanol: An Update.** Agricultural Economic Report No. 814. 2002.

C-174 Vink, et al. "The eco-profiles for current and near-future NatureWorks® polylactide (PLA) production." **Industrial Biotechnology**. Volume 3, Number 1, 2007, pp. 58-81.

APPENDIX D

FABRICATION PROCESSES

INTRODUCTION

This appendix includes data for fabrication processes that convert the materials into the containers and packaging materials. The following processes are addressed in this appendix:

- PET Blow Molding
- PLA Blow Molding
- Plastic Closure Injection Molding
- Reusable Plastic Container Fabrication
- Reusable Steel Container Fabrication
- Reusable Aluminum Container Fabrication
- Corrugated Paperboard for Trays and Boxes
- Plastic Film Extrusion

Production of the materials used in these fabrication processes is described in Appendix C. There is no discrete boundary between glass melting and production of glass containers, so production of glass containers has been discussed with glass production in Appendix C.

PET STRETCH BLOW MOLDING

Before a plastic material can be used in a blow molding process, it is molded into a preform using the injection mold process. Stretch blow molding is comprised of three main steps: injection, blowing, and ejection. This process is commonly used to produce hollow plastic objects such as PET bottles. An extruder barrel and screw assembly is used to melt the polymer. Once melted, the material is injected into a hollow mold that is heated. The preformed mold determines the external shape while a mandrel (core rod) forms the inside shape. The preformed mold is clamped around the core rod. The mold opens, allowing compressed air into the preform, inflating it to its final shape. The material is cooled, the mold is opened, and the core rod is rotated to eject the finished product.

The preform is made up of a fully formed bottle/jar neck with a thick tube of polymer attached, which eventually forms the body. The preform is heated above the polymer's glass transition temperature and stretched mechanically with a core rod. First, low pressure air (70 to 350 psi) is introduced, blowing a 'bubble.' After the stretch rod is fully extended, high pressure air (580 psi) blows the expanded plastic bubble into the shape of the blow mold.

A common polymer used in stretch blow molding, polyethylene terephthalate (PET), is strengthened when stretched, allowing it to keep its shape under pressures created by carbonated beverages. Data for the stretch blow molding of 1,000 pounds of PET bottles are shown in Table D-1.

Table D-1

DATA FOR THE BLOW MOLDING OF
1,000 LBS OF PET BOTTLES

Raw Materials			
PET resin (pellets)	1,001	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	546	kwh	5619
Total Process			5619
Environmental Emissions			
Solid Wastes	1.00	lb	

References: D-1 and D-2

Source: Franklin Associates, A Division of ERG

PLA BLOW MOLDING

Data specific to the blow molding of PLA bottles are not available. PLA bottles can be fabricated on the same equipment that is used for the blow molding of PET bottles, so Franklin Associates adapted the data for the energy requirements of PET bottle blow molding to account for the lower temperature requirements for PLA bottle blow molding (References D-3 and D-4). Franklin Associates also adapted the data for solid waste from PLA bottle blow molding to account for the wastes caused by the relatively stringent processing requirements of PLA blow molding (References D-3 and D-4). Data for the blow molding of 1,000 pounds of PLA bottles are shown in Table D-2.

Table D-2

DATA FOR THE BLOW MOLDING OF
1,000 LBS OF PLA BOTTLES

			Total Energy Thousand Btu
Raw Materials			
PLA resin (pellets)	1,002	lb	
Energy Usage			
Process Energy			
Electricity	491	kwh	5057
Total Process			5057
Environmental Emissions			
Solid Wastes	2.00	lb	

References: D-1 through D-4

Source: Franklin Associates, A Division of ERG

PLASTIC CLOSURE INJECTION MOLDING

Injection molding is the process of turning plastic resin into parts that range from very simple to highly complex in shape. For this manufacturing process, plastic is fed by a rotating screw under high pressure into a mold that is the inverse shape of the desired product shape. The melted plastic solidifies when it comes into contact with the cooled wall of the mold. The mold opens and the finished part is ejected, completing the cycle.

Polypropylene is a plastic commonly used for injection molding. Injection molding data are based on confidential industry data (Reference D-1) collected from 1992 through 2005 and APME data collected in the 1990s (Reference D-2).

Data for the injection molding of 1,000 pounds of plastic are shown in Table D-3. For modeling purposes, it is assumed that the closure molder is located within a 200 mile distance of the filler.

Table D-3

DATA FOR THE INJECTION MOLDING OF 1,000 LBS OF POLYPROPYLENE

			Total Energy Thousand Btu
Raw Materials			
Polypropylene	1,005	lb	
Energy Usage			
Process Energy			
Electricity	951	kwh	9790
Total Process			9790
Transportation Energy			
Combination truck	100	ton-miles	
Diesel	1.05	gal	167
Environmental Emissions			
Solid Wastes	5.00	lb	

References: D-1 and D-2

Source: Franklin Associates, A Division of ERG

REUSABLE PLASTIC CONTAINER FABRICATION

Hollow plastic parts are formed by a process called blow molding. Melted plastic is extruded into a hollow tube (a parison) and captured by closing it into a cooled metal mold. Low-pressure air (typically 25 to 150 psi) is blown into the parison, inflating it into the shape of the desired container. Once the plastic has cooled, the mold can be opened and the part ejected.

Reusable plastic drinking containers made of polyester copolymer (modeled here as PET) and HOD bottles made of PET or polycarbonate are produced by blow molding. Data for blow molding of polycarbonate HOD bottles is based on data from a confidential supplier. Data for blow molding of reusable polyester copolymer drinking containers or PET HOD bottles are based on confidential industry data collected by Franklin Associates from 1992 through 2005, PlasticsEurope blow molding data from a 2005 report, and Ecoinvent blow molding data. Data for polycarbonate HOD bottles are shown in Table D-4a, and data for polyester copolymer and PET bottles are shown in Table D-4b. For modeling purposes, it is assumed that the containers are molded within a 500 mile distance from the filler or consumer.

Table D-4a

DATA FOR THE FABRICATION OF
1,000 LBS OF REUSABLE POLYCARBONATE HOD CONTAINERS

			Total Energy Thousand Btu
Raw Materials			
Plastic resin (polycarbonate)	1,007	lb	
Energy Usage			
Process Energy			
Electricity	954	kwh	9,818
Total Process			9,818
Transportation Energy			
Combination truck	250	ton-miles	
Diesel	2.63	gal	417
Total Transportation			417
Environmental Emissions			
Solid Wastes	7.00	lb	

Reference: D-1.

Source: Franklin Associates, A Division of ERG

Table D-4b

DATA FOR THE FABRICATION OF
1,000 LBS OF REUSABLE POLYESTER CONTAINERS
(Individual reusable containers or HOD containers)

			Total Energy Thousand Btu
Raw Materials			
Plastic resin (polyester)	1,007	lb	
Energy Usage			
Process Energy			
Electricity	775	kwh	7,976
Total Process			7,976
Transportation Energy			
Combination truck	250	ton-miles	
Diesel	2.63	gal	417
Total Transportation			417
Environmental Emissions			
Solid Wastes	7.00	lb	

References: D-1 and D-2

Source: Franklin Associates, A Division of ERG

REUSABLE STEEL CONTAINER FABRICATION

This analysis assumes that electric furnaces are used for the fabrication of reusable steel containers, which can process virgin metal or recovered scrap (Reference D-5). Metal casting generates particulates and hazardous gaseous compounds. Manufacturers use forced air or vacuum fume collection systems to capture these emissions before plant air is returned to the environment (Reference D-9). Metal casting also generates waterborne emissions. This analysis estimated waterborne emissions based on metal caster effluent limitations (Reference D-5).

This analysis assumes that the metals and additives used for producing stainless steels and other alloys do not account for a significant share of environmental burdens in the life cycle of water delivery systems (Reference D-3), and therefore these are not included. Data for the casting and finishing of reusable steel containers are shown in Table D-5.

Based on internet searches for steel water bottle producers, the majority of reusable steel water bottles appear to be manufactured in China. For the purpose of this analysis, transportation steps were estimated as 200 miles from manufacturer to port (using Shanghai), 6,587 miles by ocean transport (Shanghai to Los Angeles) and 918 miles by truck from Los Angeles to Salem, Oregon. Research of Chinese steel production is outside the scope of this analysis; Chinese steel production will be modeled based on U.S. processes described in Appendix C and using the Chinese grid to model the burdens for electricity used in steel production and container manufacture. Since the weight of one container is small, and the production and transport burdens for the container will be divided over hundreds of lifetime uses, the simplifying assumptions for modeling container production are expected to have a minimal influence on results.

Table D-5

**DATA FOR THE FABRICATION OF
1,000 LBS OF REUSABLE STEEL CONTAINERS**

			Total Energy Thousand Btu
Raw Materials			
BOF Steel Sheet	1,001	lb	
Energy Usage			
Process Energy			
Electricity	383	kwh	3,945
Total Process			3,945
Transportation Energy			
Combination truck (total)	559	ton-miles	
Diesel	5.87	gal	932
Ocean freighter	3,294	ton-miles	
Diesel	0.63	gal	99
Residual	5.63	gal	966
Total Transportation			1,998
Environmental Emissions			
Atmospheric Emissions			
Particulates	0.15	lb	
Carbon monoxide	0.50	lb	
VOCs	0.030	lb	
Lead	0.0050	lb	
Solid Wastes	1.00	lb	
Waterborne Wastes			
Copper	2.9E-05	lb	
Lead	7.1E-05	lb	
Zinc	1.0E-04	lb	
Oils and grease	0.0018	lb	
TSS	0.0027	lb	

References: D-5

Source: Franklin Associates, A Division of ERG

REUSABLE ALUMINUM CONTAINER FABRICATION

This analysis assumes that electric furnaces are used for the fabrication of reusable aluminum containers, which can process virgin metal or recovered scrap (Reference D-5). This analysis assumes that the energy and material inputs and outputs for the fabrication of reusable aluminum containers are similar to the casting and finishing of reusable steel containers. Data for the casting and finishing of reusable aluminum containers are shown in Table D-6.

Based on internet searches, SIGG containers manufactured in Switzerland are the most commonly used aluminum water bottles. For the purpose of this analysis, transportation steps were estimated as 315 miles from manufacturer (Frauenfeld, Switzerland) to port (using Genova, Italy), 4,634 miles by ocean transport (Genova to New York) and 2,994 miles by truck from New York to Salem, Oregon. This is the most direct route, although transport could also occur by ocean from European port to a West Coast port and by truck to Oregon. The shortest distance route modeled in this analysis uses more truck transport, while the alternate route would require more ocean miles but fewer truck miles.

Research of European aluminum production is outside the scope of this analysis; European aluminum production will be modeled based on U.S. processes described in Appendix C and using the European grid to model the burdens for electricity used in container manufacture. Since the weight of one container is small, and the production and transport burdens for the container will be divided over hundreds of lifetime uses, the simplifying assumptions for modeling container production are expected to have a minimal influence on results.

Table D-6

DATA FOR THE FABRICATION OF
1,000 LBS OF REUSABLE ALUMINUM CONTAINERS

			Total Energy Thousand Btu
Raw Materials			
Primary aluminum ingot	1,001	lb	
Energy Usage			
Process Energy			
Electricity	383	kwh	3,945
Total Process			3,945
Transportation Energy			
Combination truck (total)	1,655	ton-miles	
Diesel	17.37	gal	2,759
Ocean freighter	2,317	ton-miles	
Diesel	0.44	gal	70
Residual	3.96	gal	680
Total Transportation			3,509
Environmental Emissions			
Atmospheric Emissions			
Particulates	0.15	lb	
Carbon monoxide	0.50	lb	
VOCs	0.030	lb	
Lead	0.0050	lb	
Solid Wastes	1.00	lb	
Waterborne Wastes			
Copper	2.9E-05	lb	
Lead	7.1E-05	lb	
Zinc	1.0E-04	lb	
Oils and grease	0.0018	lb	
TSS	0.0027	lb	

References: D-5

Source: Franklin Associates, A Division of ERG

CORRUGATED TRAY FABRICATION

Rolls of linerboard and medium are sent to a box plant. The medium is softened by heat and steam and then drawn through a pair of gear-like cylinders to produce the flutes. Adhesive is added to one side of the flutes, and a linerboard is pressed to that side. Then the exposed flutes have adhesive added, and a linerboard is pressed to the other side. This is a single-face corrugated board. Depending on the strength needed for the box, a double-face (2 flutes, 3 linerboards) or triple-face (3 flutes, 4 linerboards) board can be produced. The board is then cut into flat sheets in various sizes, depending on the box size needed. The sheets are stacked and the adhesive is allowed to dry (Reference D-10).

Converting machines are used to convert corrugated boards into boxes. The converter can use a die-cut machine to cut the board into a pattern and the box-user will fold and glue the box. The converter can also use a flexo-folder gluer to completely produce the box and then ship it flat to the box-user (Reference D-10).

Data for the fabrication of corrugated trays or boxes are shown in Table D-7.

Table D-7

**DATA FOR THE CONVERSION
OF CORRUGATED TRAYS OR BOXES**

Raw Materials			
Semichemical medium	187	lb	
Recycled medium	130	lb	
Virgin linerboard	542	lb	
Recycled linerboard	141	lb	
Corn starch adhesive	16.7	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	39.2	kwh	403
Natural gas	391	cu ft	438
Total Process			841
Transportation Energy			
Combination truck	100	ton-miles	
Diesel	1.05	gal	167
Total Transportation			167
Environmental Emissions			
Atmospheric Emissions			
Particulates	1.00		
Solid Wastes	5.00	lb	
Waterborne Wastes			
BOD	0.10	lb	
COD	0.15	lb	
Suspended solids	0.10	lb	

References: D-6

Source: Franklin Associates, A Division of ERG

PLASTIC FILM EXTRUSION

Plastics extrusion is a manufacturing process in which raw plastic material is melted and formed into a continuous profile. In the extrusion of plastics, resin is gravity fed from a top-mounted hopper into the barrel of the extruder. The material enters through the feed throat and comes in contact with the screw. The rotating screw (turning at approximately 120 rpm) forces the resin into a heated barrel. The molten plastic leaves the screw and travels through a screen that removes contaminants. The molten plastic is then forced through an annular slit die, usually vertically, to form a thin walled tube. Air is blown through a hole in the center of the die to blow up the tube. A high-speed air ring is on top of the die and blows onto the hot film to cool it. The tube of film then continues upwards, continually cooling, until it passes through nip rolls where the tube is flattened. The edges of the tube are slit to produce two flat film sheets. The film is then wound onto reels.

Data for film extrusion are based on confidential industry data (Reference D-1) collected from 1992 through 2005 and APME data collected in the 1990s (Reference D-2). These data are shown in Table D-8. For the purposes of this analysis, it is assumed that the film supplier is located within 200 miles of the facility where the film is used for packaging.

Table D-8

DATA FOR THE EXTRUSION OF POLYETHYLENE FILM

Raw Materials			
Polyethylene resin (LDPE or LLDPE)	1,010	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	193	kwh	1,986
Total Process			1,986
Transportation Energy			
Combination truck	100	ton-miles	
Diesel	1.05	gal	167
Total Transportation			167
Environmental Emissions			
Solid Wastes	10.0	lb	

References: D-7 and D-8

Source: Franklin Associates, A Division of ERG

REFERENCES

D-1 Franklin Associates, A Division of ERG. Data from industry sources collected from 1992 through 2005.

D-2 Boustead. **Eco-Profiles of the European Plastics Industry, Report 10: Polymer Conversion.** Association of Plastics Manufacturers in Europe (APME). 1997.

D-3 Assumption by Franklin Associates based on data for similar processes, September 2008.

D-4 Nature Works® PLA ISBM Bottle Guide

D-5 **Energy and Environmental Profile of the U.S. Metal Casting Industry**; Prepared by Energetics, Inc., Prepared for U.S. Department of Energy Office of Industrial Technologies. September 1999. (Chapters 4 and 7)

D-6 Savolanine, Antti. Paper and Paperboard Converting. Fapet Oy. Helsinki, Finland. 1998.

D-7 Bezigian, Thomas. **Extrusion Coating Manual, 4th Edition.** Tappi Press, Atlanta, Georgia. 1999.

D-8 **APME. Polyethylene (LD) Film.** Information produced in collaboration with European Plastics Converters and European Committee of Machine Manufacturers for Plastics and Rubber Industries. 1993.

D-9 Vehicle Recycling Partnership (VRP). 2003.

D-10 Information from the website: www.tappi.org/paperu/all_about_paper/earth_answers/EarthAnswers_HowBoxes.pdf

APPENDIX E

DRINKING WATER TREATMENT

INTRODUCTION

This appendix shows the data for the municipal treatment and distribution of water for drinking, as well as the pumping of well water for drinking. Additional water treatment processes (such as filtration, reverse osmosis, ozonation, and UV treatment) may be performed by water bottlers and are thus discussed separately in Appendix F, which details the processes related to the filling of bottled water.

WATER TREATMENT

Both municipal utilities and private wells are sources of drinking water. Municipal water can be delivered directly to a home, or in the form of locally bottled water; private wells are a source of direct tap water for 25 percent of Oregon's population.

Utilities get fresh water from either groundwater or surface water sources, which they treat as necessary and distribute to customers. In Oregon, the largest water treatment utilities such as Portland, Eugene and Salem all use surface water as their primary source. Depending on the turbidity, microbial content and pH of the incoming water, the water can be treated with chemicals such as alum for coagulation, filtered through sand or membranes and disinfected with some form of chlorine.

Overall energy use by water treatment plants is taken from survey data collected by the American Water Works Association (AWWA) (Reference E-1). The data represent a wide range of water sources, utility sizes and treatment methods, not all of which may correspond with utilities in Oregon. However, it was felt that a more accurate representation of the several thousand drinking water sources in Oregon could be obtained from the AWWA data than from surveying a handful of utilities.

Energy

The primary data source for municipal water treatment is a survey of several hundred utilities across the country, which was done by the AWWA. The survey responses were filtered by the same criteria used by the AWWA; a few additional plants excluded due to suspect responses. In total, the responses from 120 utilities were used. These utilities provided information on the average daily flow, as well as how much electricity and other fuels were purchased.

To determine the total amount of energy used for each million gallons of water treated and delivered to municipal customers, the data were first examined for any log-normal behavior. While life cycle studies rarely deal with more than a handful of data points for each variable, the large number available here meant that a more statistical approach was possible. While the total energy per million gallons did have a long tail, a strong log-normal trend was not evident. As a result, both the geometric mean and a weighted average (based on the amount of water treated by each plant) were tested against the actual energy used in each plant; the weighted average better predicted the actual energy used by each of the plants. This energy use is shown in Table E-1.

Because leaks and breakages occur in municipal water lines, a loss factor is applied in the life cycle model to account for the additional water that must be treated and pumped in order to deliver 1,000 gallons at the consumer's tap. A 15 percent loss was used, based on a 2001 report available from the American Water Works Association (Reference E-8).

Approximately 25 percent of households in Oregon get their water from wells; thus, tap water for Oregon is based on 75 percent municipal water and 25 percent well water. The energy required to pump water from private wells was developed based on specifications for pumps manufactured by Franklin Electric (Reference E-2). Using these specifications, and an assumption that a typical family requires a pump with 12 gallon per minute (Reference E-3), energy requirements for pumping one million gallons were developed. These energy requirements are listed in Table E-2.

All grid electricity in this appendix is representative of an Oregon specific mix. It is assumed that all bottled municipal water will originate in Oregon; in cases where this assumption is not valid, the bottled water will likely come from neighboring states with similar electricity grid mixes.

Chemical Use

Water treatment plants in Oregon use a variety of chemical additives to prepare water for public consumption. Portland uses chlorine and chloramine for disinfection, with sodium hydroxide for pH adjustment; Eugene adds alum for coagulation and disinfects with a gaseous chlorine process, finishing with sodium hydroxide for pH adjustment; and Salem fluoridates its water, adding soda ash for pH adjustment and hypochlorite for disinfection (Reference E-3).

Because none of the chemicals are used in large amounts, a sensitivity analysis showed that their cumulative impact on energy use in water treatment will likely be less than 10 percent. To simplify the process, it has been assumed that concentration of chlorine is 3 mg/l, ammonia is 0.4 mg/l and sodium hydroxide is 5 mg/l. These are the approximate concentrations used by Portland in the treatment of their water (Reference E-6). The total amount of each chemical used to treat one million gallons is shown in table E-1.

While it may be necessary to disinfect a well on occasion, the water does not require constant treatment. Instead, shock chlorination is used for a new well, and after any positive tests for bacteria. Tests are performed annually, or if there is a change in taste, color or odor of the water. The amount of chlorine required for this disinfection is likely to be less than 0.1 pounds, and so will be excluded (Reference E-4).

Table E-1

DATA FOR THE TREATMENT AND DELIVERY OF 1,000,000 GALLONS MUNICIPAL WATER

Raw Materials			
Chlorine	27	lb	
Ammonia	3	lb	
Caustic	43	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	1,417	kwh	14,582
Natural gas	405	cu ft	454
Total Process			15,036

References: E-1, E-5

Source: Franklin Associates, A Division of ERG

Table E-2

DATA FOR THE PUMPING OF 1,000,000 GALLONS WELL WATER

Energy Usage			**Energy Thousand Btu**
Process Energy			
Electricity (grid)	2,071	kwh	21,310
Total Process			21,310

References: E-2, E-3

Source: Franklin Associates, A Division of ERG

Carbon Dioxide Release

It has been documented that dissolved CO_2 in groundwater from unconfined aquifers can be one to two orders of magnitude higher than those found in surface water (Reference E-7). While these studies have focused specifically on groundwater from Texas and the Midwest, the results are anticipated to hold for all geographic regions. Table E-3 shows the estimated range of CO_2 that may be released from 1,000 gallons of extracted groundwater.

Table E-3

DATA FOR THE RELEASE OF CARBON DIOXIDE FROM 1,000 GALLONS GROUNDWATER

CO2 Released from Groundwater	
Low estimate:	8.5 lb
High estimate:	85 lb

Reference: E-7

Source: Franklin Associates, A Division of ERG

REFERENCES

E-1 *Energy Index Development for Benchmarking Water and Wastewater Utilities*. AWWA Research Foundation. 2007.

E-2 Franklin Electric AIM Manual. Accessible at http://www.franklin-electric.com/business/WaterSystems/service/AIM/default.aspx.

E-3 wellcare® Information for You Sizing a Well Pump. Accessible at http://www.wellcarehotline.org/VAiWebDocs/WSCDocs/2567958WSC_INST_20.pdf.

E-4 wellcare® Information for You About Disinfecting Your Well. Accessible at http://www.wellcarehotline.org/VAiWebDocs/WSCDocs/6055720Disinfecting_Your_Well_FINAL.pdf.

E-5 Oregon Safe Drinking Water Information System. Accessible at http://oregon.gov/DHS/ph/dwp/index.shtml.

E-6 Personal communication with Yone Akagi, Regulatory Compliance Manager at the Portland Water Bureau. September 25, 2008.

E-7 Personal communication with Dr. Gwen Macpherson, Associate Professor of Geology, University of Kansas. October 31, 2008.

E-8 AWWA 20244. "Plain Talk About Drinking Water: Questions and Answers about the Water You Drink." 2001.

APPENDIX F

WATER BOTTLING OPERATIONS

INTRODUCTION

The purpose of this appendix is to show data related to the operations at a bottled water facility. This includes the activities of purifying water (if applicable) and filling bottles. The following processes are described in this appendix:

- Water Filtration
- Reverse Osmosis Purification
- Ozone Treatment
- UV (Ultraviolet) Disinfection
- Bottle Filling

This analysis includes the bottling of water acquired from municipal sources as well as the bottling of water that is acquired directly from natural sources (e.g., spring or artesian water). When water is acquired from municipal sources, bottlers run it through additional purification processes, which may include filtration, reverse osmosis, and UV disinfection. When water is acquired directly from natural sources, bottlers perform a minimal amount of water treatment processes, such as UV or ozone treatment to assure disinfection, before filling containers. Energy and material use for various water treatment processes are described in the following sections. In the LCI modeling, electricity use for water treatment and filling processes performed in Oregon will be modeled using the Oregon-specific grid mix.

WATER FILTRATION

The purpose of filtration is to remove different types of particles, suspended solids, colloidal compounds, and biological species from water. Filtration is a physical process that employs various media, such as screens, membranes, or granular materials (Reference F-1).

The most common filters used for water treatment are mass media filters, which can include rapid sand filters, slow sand filters, pressure or gravity filters, diatomaceous earth filters, or combinations thereof (Reference F-1).

No data are available for the energy requirements for water filtration. Since water filtration is a physical process, requiring no heat exchange or material transformation activities, it is assumed to have low energy requirements in comparison to other activities at a water bottling plant. Omitting energy requirements for filtration is expected to have a minimal effect on study results.

REVERSE OSMOSIS PURIFICATION

Reverse osmosis is a diffusion-controlled membrane process that is effective at removing organic compounds from water (Reference F-1). Membranes (which can be in the form of flat sheets, hollow fibers, or coated tubes) are the key components of reverse osmosis systems (Reference F-1). A typical reverse osmosis process requires a pump, membranes in a housing element, control valves, and sensors (including pressure gauges and flow meters) (Reference F-1). Data for reverse osmosis are shown in Table F-1.

Table F-1

DATA FOR THE
REVERSE OSMOSIS OF 1,000 GALLONS OF WATER

Raw Materials		
Water (from filtration process)	1,250	gal
Energy Usage		
Process Energy		
Electricity	24.5	kwh
Environmental Emissions		
Waterborne Wastes (1)		
Organics unspecified	0.010	lb
Effluent water volume	250	gal

(1) Water effluents results from the discharge of "reject water" from the reverse osmosis process. Organics are assumed to be in source water at a concentration of 1 ppm.

References: F-1 through F-3.

Source: Franklin Associates, A Division of ERG

OZONE TREATMENT

Ozone treatment is a chemical oxidation process that uses ozone to oxidize reduced inorganic species (Reference F-1). The purpose of ozone treatment is to destroy compounds that can cause undesirable tastes and odors. In particular, ozone treatment is widely used in the bottled water industry to remove dissolved iron or manganese (Reference F-1). Ozone is an unstable molecule and must be generated at the site of application. It is generated by passing dry air or oxygen through a high-voltage electric field. Data for ozone treatment of water are shown in Table F-2.

Table F-2

DATA FOR THE
OZONE TREATMENT OF 1,000 GALLONS OF WATER

Raw Materials		
Water (from reverse osmosis process)	1,000	gal
Ozone	0.0033	lb
Energy Usage		
Process Energy		
Electricity	0.64	kwh

(1) Data for the production of ozone are provided in Appendix I, Table I-4.

References: F-1 and F-7.

Source: Franklin Associates, A Division of ERG

ULTRAVIOLET DISINFECTION

UV irradiation is an antimicrobial treatment method that disinfects water by degrading the nucleic acid in bacterial cells. Most UV disinfection units have a tubular arrangement that pass water by a perpendicularly-mounted mercury discharge lamp (Reference F-1). The UV light source is enclosed in a protective quartz glass sleeve and mounted so that UV rays are absorbed into the water as it flows past the lamp. Reported bulb lifespans are in the range of 8,000 to 9,000 hours. No data are available on the production or disposal of the mercury lamps. Data for ultraviolet disinfection of water are shown in Table F-3.

Table F-3

DATA FOR THE
UV DISINFECTION OF 1,000 GALLONS OF WATER

Raw Materials		
Water (from ozone treatment)	1,000	gal
Energy Usage		
Process Energy		
Electricity	0.050	kwh

References: F-4 through F-6.

Source: Franklin Associates, A Division of ERG

BOTTLE FILLING

Bottle filling is a mechanical process during which empty bottles are cleaned, filled with water, and capped.

For single serving bottles that are manufactured off-site (which is the case for glass bottles or for bottlers who purchase fabricated plastic bottles), the bottles are rinsed or cleaned with an air blast before filling them with water (Reference F-1). Less than 0.2 ounces (5 milliliters) of water are used to rinse a 16.9 ounce (500 milliliter) bottle prior to filling (Reference F-8).

Water that is used for rinsing operations is not recycled within the bottling facility but is discharged to the drain. While a bottling plant may have the capability to recover and purify rinse water, it is likely that the purity of the rinse water after use is significantly lower than the purity of the water coming into the plant (Reference F-2). The recovery and purification of rinse water could also lead to cross-contamination between processing operations and the product water.

For 5-gallon HOD containers, the washing and rinsing of containers prior to filling are addressed in Appendix I.

Data for the filling of containers are assumed to be same for equal volumes of filled 16.9 ounce (500 milliliter) bottles and filled 5-gallon HOD containers. It is also assumed that filling energy is comparable for containers of different materials, such as PET and glass. Data for the filling of 16.9-ounce single serving containers with water are shown in Table F-4a, and data for the filling of 5-gallon HOD containers with water are shown in Table F-4b.

Table F-4a

**DATA FOR THE FILLING OF
SINGLE-SERVING CONTAINERS WITH 1,000 GALLONS OF WATER**

	Bottles filled without rinsing (1)	Bottles rinsed before filling
Raw Materials		
Water (from UV disinfection process or natural source)	1,000 gal	1,010 gal
Energy Usage		
Process Energy		
Electricity	2.70 kwh	2.70 kwh
Total Process		
Environmental Emissions		
Effluent water volume	0 gal	10.0 gal

(1) Not all bottles are rinsed prior to filling. Single serving bottles fabricated at the filling site may not require rinsing prior to filling. Bottles may also be cleaned with a blast of air rather than by rinsing, according to one bottler.

References: F-7 and F-8.

Source: Franklin Associates, A Division of ERG

Table F-4b

**DATA FOR THE FILLING OF
5-GAL CONTAINERS WITH 1,000 GALLONS OF WATER**

Raw Materials	
Water (from UV disinfection process or natural source)	1,000 gal
Energy Usage	
Process Energy	
Electricity	2.70 kwh

References: F-7.

Source: Franklin Associates, A Division of ERG

REFERENCES

F-1 Senior, D.S. and Dege, N. **Technology of Bottled Water, Second Edition.** Chapter 5: Water Treatments.

F-2 Assumption by Franklin Associates, October 2008.

F-3 Saving Energy, Water, and Money with Efficient Water Treatment Technologies. Federal Energy Management Program. DOE/EE-0294. (www.eere.energy.gov/femp/)

F-4 Equipment specifications from UV-Consulting Peschl. Accessed on October 6, 2008 at www.uv-consutling.de.

F-5 Drainage Services Department, Hong Kong Special Administrative Region of The People's Republic of China, **Peng Chau Sewage Treatment Works Upgrade - Investigation, Design and Construction.** Agreement No. CE 83/2001(DS). Appendix 2B: Life Cycle Analysis for Chlorination and UV Disinfection. August 2004.

F-6 **Energy and Water for Sustainable Living: A Compendium of Energy and Water Success Stories.** Prepared by Argonne National Laboratory for U.S. Department of Energy, U.S. Department of State, and U.S. Agency for International Development, July 2002 (Available electronically at http://www.pi.energy.gov)

F-7 Electric process energy consumption data provided by a confidential water bottler. Pennsylvania. 2006.

F-8 Phone interview with representative of Norland International Inc, Lincoln, Nebraska; September 26, 2008.

APPENDIX G

BOTTLED WATER DISTRIBUTION

INTRODUCTION

The purpose of this appendix is to show data related to the distribution of filled bottles. The distribution of filled bottles includes transport by road or ocean freight, depending on the geographies of where water is sourced. The data shown in this appendix represents the life cycle phase after the filling of bottles and preceding the cooling and consumption of water. The following distribution steps are described in this appendix:

- Transport of filled, single-serving plastic bottles (including PET and PLA bottles) from filler to retailer.
- Transport of filled, single-serving glass bottles from filler to retailer.
- Transport of filled, 5-gallon containers via delivery truck from filler to home or office and back to filler.

The distribution steps described in this appendix include the energy to transport water, containers, and associated packaging (corrugated trays and plastic stretch wrap). As is the case with all transportation data in this analysis, this appendix expresses transportation requirements in terms of ton-miles (the movement of one ton of material a distance of one mile). This is the preferred basis for expressing transportation energy because it accounts for both the weight of cargo and the distance traveled. The use of a functional unit (e.g., the delivery of 1,000 gallons of water) converts all material and energy flows to a common basis. Thus, while the functional unit is not apparent in this appendix, Franklin Associates' LCI model does account for the fact that one ton-mile of filled plastic bottles and one ton-mile of filled glass bottles represent the same transportation energy (assuming the same mode of transportation is used by the two alternatives), but represent a greater quantity of delivered water for the plastic systems because plastic bottles have a lower package to product ratio than glass bottles.

In addition to expressing transportation requirements on the basis of ton-miles, this appendix shows all data on the basis of the transport of 1,000 pounds of product (which in this case is an aggregate of water, containers, and other packaging). Again, while the functional unit of this analysis is not apparent in the following data, the LCI model uses the system weight data shown in Appendix B and the density of water to normalize the transportation requirements to the basis of a delivered volume of drinking water.

Franklin Associates' LCI model also accounts for shipments of cargo that are "volume limited" instead of "weight limited." When a shipment is volume limited, the total volume of the vehicle is filled before the maximum weight limit of the vehicle is reached; this occurs when cargo has a low density. Examples of products that have relatively low densities and cause volume-limited transport are foam materials or large-diameter plastic pipe. Bottled water is a dense product, and thus the shipment of bottled water by road or ocean freight is not volume limited (Reference G-1).

The transportation requirements for shipping bottled water from fillers using commercial vehicles are discussed below. Sensitivity analysis on consumer travel to stores to purchase bottled water is included in the life cycle modeling and is described in the Methodology chapter, Chapter 1.

TRANSPORT OF SINGLE-SERVING PLASTIC BOTTLES

This analysis includes single-serving plastic bottles that are filled with natural or purified municipal water in Oregon, and natural water from Maine and the South Pacific. The transportation requirements for the distribution of filled, single-serving plastic bottles (which include PET and PLA bottles) are shown in Table G-1.

Table G-1

DATA FOR THE DISTRIBUTION OF
1,000 LBS OF FILLED, SINGLE-SERVING PLASTIC BOTTLES

Source:	Redmond, OR (natural water)		Portland, OR (purified municipal water)		Lewiston, ME		Suva, Fiji (natural water)	
Intermediate Port:	none		none		none		Los Angeles, CA	
Destination:	Salem, OR		Salem, OR		Salem, OR		Salem, OR	
Raw Materials								
Filled plastic bottles and other packaging	1,000	lb	1,000	lb	1,000	lb	1,000	lb
Energy Usage								
Transportation Energy								
Combination truck	65.0	ton-miles	25	ton-miles	1,634	ton-miles	461	ton-miles
Diesel	0.68	gal	0.26	gal	17.2	gal	4.84	gal
Ocean freighter	0	ton-miles	0	ton-miles	0	ton-miles	2,398	ton-miles
Diesel	0	gal	0	gal	0	gal	0.46	gal
Residual	0	gal	0	gal	0	gal	4.10	gal

References: G-1 through G-4

Source: Franklin Associates, A Division of ERG

TRANSPORT OF SINGLE-SERVING GLASS BOTTLES

This analysis includes single-serving glass bottles that are filled with natural water in France. The purpose of including such a system is to account for the distribution of imported water in glass bottles. The transportation requirements for the distribution of filled, single-serving glass bottles are shown in Table G-2.

Table G-2

DATA FOR THE DISTRIBUTION OF 1,000 LBS OF FILLED, SINGLE-SERVING GLASS BOTTLES

Source:	LeHavre, France (natural water)	
Intermediate Port:	New York, NY	
Destination:	Salem, OR	
Raw Materials		
Filled glass bottles and other packaging	1,000	lb
Transportation Energy		
Combination truck	1,471	ton-miles
Diesel	15.4	gal
Ocean freighter	1,598	ton-miles
Diesel	0.30	gal
Residual	2.73	gal

References: G-1 through G-4

Source: Franklin Associates, A Division of ERG

TRANSPORT OF FIVE GALLON CONTAINERS

This analysis includes multi-serving plastic containers that are filled by HOD (home and office delivery) bottlers and delivered to homes and offices via route trucks. This includes water that is sourced in Oregon and water that is sourced in Maine. The transportation requirements for the distribution of filled, multi-serving plastic containers are shown in Table G-3. The transportation distances shown include transportation from the filler to a distribution center and delivery on a route truck, which picks up empty bottles as filled bottles are dropped off. For the purposes of this analysis, a distance of 200 miles round trip is used for the delivery route.

Table G-3

**DATA FOR THE DISTRIBUTION OF
1,000 LBS OF FILLED, 5-GALLON CONTAINERS**

	Redmond, OR	
Source:	(natural water)	
Destination:	Salem, OR	
Raw Materials		
Filled plastic containers and other packaging	1,000	lb
Transportation Energy		
Combination truck	65.0	ton-miles
Diesel	0.68	gal
Single unit truck	100	ton-miles
Diesel	2.25	gal

Reference: G-1

Source: Franklin Associates, A Division of ERG

REFERENCES

G-1 Assumption by Franklin Associates, based on the weights of filled water bottles. September, 2008.

G-2 **CIA World Fact Book.** https://www.cia.gov/library/publications/the-world-factbook (Accessed September 13, 2008)

G-3 **Google Maps.** http://maps.google.com (Accessed September 13, 2008).

G-4 **World Ports Distances.** http://www.distances.com (Accessed September 13, 2008)

APPENDIX H

DRINKING WATER COOLING PROCESSES

INTRODUCTION

Whether it is consumed from a disposable bottle or a reusable container, consumers can choose to drink water chilled or at room temperature. This appendix describes the processes used to cool drinking water. Four processes for the cooling of water have been identified: (1) retail refrigeration, (2) water coolers, (3) residential refrigerators, and (4) ice cubes. The energy requirements and, if applicable, emissions of refrigerants for each of these four cooling methods are discussed below.

RETAIL REFRIGERATION

Retail refrigeration is used for bottled water. While full cases of bottled water are typically sold at room temperature, individual bottles are often refrigerated for retail sale. It is not necessary to refrigerate water during retail storage and display; however, if a consumer wants to drink bottled water immediately, he or she will likely get it from a refrigerated retail cabinet.

The energy requirements for retail refrigeration were calculated based on energy consumption data for supermarkets. The annual electricity consumption of a supermarket in the United States is approximately 50 kWh per square foot, and 60% of supermarket electricity consumption is due to refrigeration (References H-1 and H-2).

A large supermarket has approximately 40,000 square feet of floor area (Reference H-4). To estimate the electricity used for refrigeration, it was assumed that 5% of a supermarket's floor space is occupied by refrigeration units. This assumption is necessary because if total refrigeration energy is divided by total supermarket floor area, the resulting factor allocates refrigeration energy among total floor area and thus understates the energy intensity of the area occupied by refrigerated cabinets.

Commercial refrigeration units circulate refrigerant in long networks of piping, which include many joints, valves, and compressors (Reference H-3). The many connections in a commercial refrigeration system are a source of refrigerant leaks. The emission of refrigerants was calculated based on the loss rates of refrigerants for commercial refrigeration systems. A commercial refrigeration system requires approximately 3,000 pounds of refrigerant (Reference H-4) and loses approximately 15% of its refrigerant per year (Reference H-3). The amount of refrigerants emissions per square foot of refrigerated floor space was estimated using the same method as described in the above paragraph on electricity consumption.

In addition to the rate of refrigerant leakages, the types of refrigerants that are used by supermarkets is also important. HCFC refrigerants are being phased out in favor of non-chlorinated refrigerants, but older refrigeration systems that use HCFCs are still in use at supermarkets (Reference H-3). It was thus assumed that 50% of supermarket refrigeration systems use HCFCs and remaining 50% use HFCs.

Based on the above discussion, data for the retail display of refrigerated water is shown in Table H-1. Data are expressed on the basis of cooling one square foot of space for one day.

Table H-1

DATA FOR THE REFRIGERATED STORAGE OF WATER AT SUPERMARKETS

		per sq. foot/day
Energy		
Electricity	kWh	1.644
Environmental emissions		
Emissions to air		
HFC	lbs	0.00031
HCFC (R-22)	lbs	0.00031

Source: Franklin Associates, A Division of ERG

References: H-1 through H-4

WATER COOLERS

Water coolers are used for the HOD (home and office delivery) drinking water market. A water cooler functions as a pedestal, chiller, and dispensing device for five-gallon containers of water.

The energy requirements for water coolers are based on recommendations by the US EPA Energy Star program (Reference H-5). To be certified by the Energy Star program, a water cooler must use 0.16 kWh (or less) of electricity per day if no water is withdrawn. Based on the recommendations of Premium Waters, between three and five 5-gallon bottles are used per water cooler per month, which results in an average of 2/3 gallons per day. If water is cooled from room temperature to 35 °F, an additional 193 Btu of heat is removed from the water each day. No information on the Coefficient of Performance (COP) of the heat pump was available, but assuming a low value of 2 for the COP would result in a 20% increase of cooling energy. This has not been included, but will be evaluated as a possible sensitivity if the cooling of water in this system could have a significant impact on the final results.

A water cooler has a small, closed system for circulating refrigerant. No data are available on fugitive leaks of refrigerant, but a typical water cooler does not require the replenishment of refrigerant during its lifetime. Based on this, no fugitive emissions are included.

Based on the above discussion, the energy requirements for a water cooler are shown in Table H-2. Data are expressed on the basis of chilling 1,000 gallons.

Table H-2

DATA FOR THE REFRIGERATION OF WATER BY A WATER COOLER

		per 1,000 gallons
Water input		
Bottled water (in 5 gallon containers)	gal	1000
Energy		
Electricity	kWh	240.0

Source: Franklin Associates, A Division of ERG

Reference: H-5, H-7

RESIDENTIAL REFRIGERATORS

Residential refrigerators are used for chilling bottled water or tap water in reusable containers.

The energy requirements for residential refrigerators are based on data collected by the US EPA Energy Star program, which includes the annual electricity requirements and storage volume of refrigerators sold in the United States (Reference H-6). Approximately 700 models of refrigerators and combinations of refrigerators and freezers are included in the Energy Star data. To calculate a factor for energy consumption per volume of storage, the average annual electricity consumption (X kWh/year) was divided by the average storage volume (Y cubic feet). This factor was increased by 20% to account for older, less efficient refrigerators that are currently in use. Refrigerators that are Energy Star approved use 20% less energy than prescribed by federal standards and 40% less energy than average refrigerators sold in 2001 (Reference H-6).

It is not practical to fill 100% of the volume of a refrigerator with food or beverages. It was assumed that 50% of a refrigerator's storage capacity is filled; in other words, two cubic feet of storage space holds one cubic foot of food or beverages.

A residential refrigerator has a relatively small, closed system for circulating refrigerant. A typical residential refrigerator does not require the replenishment of refrigerant during its lifetime, an indication that a negligible quantity of refrigerant leaks from residential refrigerators.

Based on the above discussion, the energy requirements for a residential refrigerator are shown in Table H-3. Data are expressed on the basis of cooling one cubic foot of space for one day.

Table H-3

DATA FOR THE RESIDENTIAL REFRIGERATION OF WATER

		per cubic foot/day
Energy		
Electricity	kWh	0.061

Source: Franklin Associates, A Division of ERG

References: H-6

ICE CUBES

Ice cubes are used for quickly chilling tap water in reusable containers. They are an alternative to chilling water in a residential refrigerator. Ice cubes are made from tap water and frozen in a residential freezer.

The energy requirements for residential freezers were calculated using a method similar to the method used to calculate the energy requirements for residential refrigerators. The US EPA Energy Star includes electricity consumption data for approximately 200 freezer-only units. Using only freezer data overlooks the use of combination refrigerator/freezer units for making ice cubes, but simplifies the allocation of energy to freezing requirements. To develop a factor for the electricity requirements per cubic feet of storage space, the average electricity consumption of freezers was divided by the average storage volume of the freezers. This factor was increased by 20% to account for older, less efficient freezers that are currently in use.

It is not practical to fill 100% of the volume of a freezer with ice cubes or other items. It was assumed that 50% of a freezer storage capacity is filled; in other words, two cubic feet of storage space holds one cubic foot of ice.

A residential freezer has a relatively small, closed system for circulating refrigerant. A typical residential freezer does not require the replenishment of refrigerant during its lifetime, an indication that a negligible quantity of refrigerant leaks from residential freezers.

Based on the above discussion, the energy requirements for the freezing and storage of ice cubes in a residential freezer are shown in Table H-4. Data are expressed on the basis of cooling one cubic foot of space for one day.

Table H-4

DATA FOR THE RESIDENTIAL FREEZING OF ICE CUBES

		per cubic foot/day
Energy		
Electricity	kWh	0.106

Source: Franklin Associates, A Division of ERG

Refercnce: H-6

REFERENCES

H-1 US EPA. Supermarkets: An Overview of Energy Use and Energy Efficiency Opportunities. (Accessed August 15, 2008 at www.energystar.gov/ia/business/challenge/learn_more/Supermarket.pdf)

H-2 US EPA. National Action Plan for Energy Efficiency Sector Collaborative on Energy Efficiency Supermarket Energy Use Profile. (Accessed August 15, 2008 at www.epa.gov/cleanrgy/documents/sector-meeting/4biii_supermarket.pdf)

H-3 US EPA. EPA Green Chill program (Accessed August 15, 2008 at http://www.epa.gov/greenchill/alttechnology.html)

H-4 IEA Annex 26: Advanced Supermarket Refrigeration/Heat Recovery Systems, Final Report Volume 1 – Executive Summary, Compiled by Van D. Baxter, Oak Ridge National Laboratory, April 2003. (Accessed August 15, 2008 at http://www.ornl.gov/~webworks/cppr/y2003/rpt/117000.pdf)

H-5 ENERGY STAR Program Requirements for Bottled Water Coolers: Version 1.1. (Accessed August 15, 2008 at http://www.energystar.gov/ia/partners/product_specs/program_reqs/water.pdf)

H-6 ENERGY STAR Qualified Refrigerators & Freezers, Last Modified: 08/08/2008. (Accessed August 15, 2008 at http://www.energystar.gov/index.cfm?c=refrig.pr_refrigerators)

H-7 http://www.premiumwaters.com/ (Accessed November 13, 2008)

APPENDIX I

CONTAINER WASHING

INTRODUCTION

The purpose of this appendix is to show data related to the washing of containers. This includes two types of systems: (1) the washing of single-serving, reusable containers in a residential dishwasher and (2) the washing of 5-gallon, reusable HOD (home and office delivery) containers by a water bottler. The following processes are described in this appendix:

- Residential Heating of Water
- Washing of Single-Serving Containers
- Washing of Five-Gallon HOD Containers

RESIDENTIAL HEATING OF WATER

For residential purposes, gas and electric heaters are the two types of water heaters. In the state of Oregon, 62% of residential water heaters are electric, 37% are gas, and 1% are other types of water heaters (Reference I-1).

Gas water heaters have a gas burner at the base that is controlled by a valve and thermostat. Gas water heaters also have a vent pipe that runs through the center of the unit and carries away exhaust gases. An electric water heater has two heating elements that are that are usually supplied by a 220 volt circuit (Reference I-2). The electric current passes over the heating elements to heat the water.

A water heater heats water on a continual basis, whether hot water is used or not. When hot water is drawn off, cold water enters the tank to replenish the tank. When the thermostat senses the water temperature has dropped below a designated temperature, it initiates the heating element(s) in an electric water heater or the burner in a gas model. Typically, the temperature can be set between 120 and 180 degrees Fahrenheit (49 to 82 degrees Celsius). It is generally recommended that the temperature is set between 120 to 140 degrees F (49 to 60 C) to prevent scalding (Reference I-3). In addition to the heating system, insulation around the tank also helps keep the water in the tank warm between heating cycles.

The EF (energy factor) can be used to measure the efficiency of a water heater. EF is the ratio of the “Rated Energy Output” to the “Total Energy Input”. The higher the EF, the more efficient the water heater. EF ratios for natural gas water heaters range from 0.6 to 0.65; EF ratios for electric water heaters range from 0.9-0.95 (Reference I-4). The EF of a water heater is determined by a standard 24-hour test developed for the U.S. Department of Energy (Reference I-4).

Data on types of water heaters in Oregon is based on phone interviews with several experts in the Oregon market. Six plumbing contractors and/or water heater suppliers provided data about the types of residential water heaters installed or sold for residential use. Data provided by each contractor was averaged to come up with the breakdown of electric, gas, and other residential water heaters in the state of Oregon. Table I-1 shows data for the residential heating of water.

Table I-1

DATA FOR THE HEATING OF
1,000 GALLONS OF WATER IN A RESIDENTIAL WATER HEATER IN OREGON

		Natural gas heater	Electric heater	Aggregated (1)
Raw Materials				
Water (from municipal source)	gal	1,000	1,000	1,000
Energy Usage				
Process Energy				
Electricity	kWh		196	123
Natural gas	cuft	972		360

(1) 63% of residential water heaters in Oregon use electricity and 37% use natural gas.

References: I-4, I-15 and I-16.

Source: Franklin Associates, A Division of ERG

WASHING OF SINGLE-SERVING REUSABLE CONTAINERS

Single-serving, reusable containers are typically washed in a residential dishwasher. A standard size dishwasher is defined as having a capacity greater than or equal to eight place settings and six serving pieces. A typical dishwashing cycle (or load) uses between 4 and 6 gallons of water to fill the basin and rinse the items (Reference I-5).

A dishwasher fills with water via an intake valve that is connected to a hot water supply line. Water temperature is further raised by an internal heating element to 130 to 140 degrees F (Reference I-6). An electric motor powers the pump to that sprays water in the dishwasher. Residential dishwashers require a 120 volt power supply (Reference I-6).

The dishwasher mixes water with an alkaline detergent; approximately 4.25 ounces of liquid dishwashing detergent is used per cycle. Data were not available on the manufacture of dishwasher detergent. A previous study on hard surface cleaners found that the energy requirements and emissions from heating water are larger than those associated with the production of the small amounts of cleaning formulations added to the water, so this exclusion is expected to have minimal effect on results (Reference I-23). However, because phosphate emissions from the use of dishwashing detergents can affect eutrophication of receiving waters, the LCA includes a sensitivity analysis on the potential contribution of detergent phosphate emissions to eutrophication impacts for the tap and HOD drinking water systems that include home washing of reusable containers.

The energy and water used by a residential dishwasher were allocated to a single-serving reusable container by determining that approximately 110 containers fit in an average residential dishwasher. The energy and water requirements per dishwashing cycle were scaled by a ratio of 1000/110 to expresses the washing requirements on the basis of 1,000 single-serving, reusable containers (Reference I-21).

Table I-2 shows data for the washing of single-serving containers in a residential dishwasher.

Table I-2

DATA FOR THE WASHING OF
1,000 SINGLE-SERVING REUSABLE CONTAINERS

		Per single dishwashing cycle		Per 1,000 containers	
		low	high	low	high
Raw Materials					
Single serving containers	containers	110	110	1,000	1,000
Hot water from residential water heater	gal	4.00	14.0	36.4	127
Detergent	lbs	0.27	0.27	2.42	2.42
Energy Usage					
Process Energy					
Electricity	kWh	1.43	1.43	13.0	13.0

References: I-11 through I-15

Source: Franklin Associates, A Division of ERG

WASHING OF FIVE-GALLON HOD CONTAINERS

This section describes the washing of HOD containers at a bottle washing facility. The transportation of HOD containers (full and empty) is characterized in Appendix G, which describes the distribution requirements for water delivery systems.

The inputs for the washing of HOD containers include water and solutions of caustic soda (sodium hydroxide), sodium hypochlorite, and ozone. The production of caustic soda is described in Appendix C and is not repeated in this appendix. The production of sodium hypochlorite and ozone are described below.

Sodium Hypochlorite Production

Sodium hypochlorite, commonly referred to as "bleach", is a cleaning agent used for the HOD container washing process. Sodium hypochlorite is produced from electrolysis of salt brine similar to the production of caustic and chlorine, except that the chlorine and caustic are not separated, but are instead allowed to mix, which facilitates the formation of sodium hypochlorite (Reference I-18). This analysis uses data for the production of sodium chlorate as a surrogate for the production of sodium hypochlorite. The production of sodium chlorate and sodium hypochlorite use the same raw materials and production technology. Data for the production of 1,000 pounds of sodium hypochlorite are shown in Table I-3.

Table I-3

DATA FOR THE PRODUCTION OF
1,000 LBS OF SODIUM HYPOCHLORITE

Raw Materials		
Salt mining	745	lb
Process Energy		
Electricity	2,400	kwh
Natural gas	3,017	cu ft
Transportation Energy		
Combination truck	100	ton-miles
Diesel	1.05	gal
Environmental Emissions		
Atmospheric Emissions		
Chlorine	0.0015	lb
Solid Wastes	0.71	lb
Waterborne Wastes		
Sodium hypochlorite	4.7E-04	lb

(1) Data in this table are for the production of sodium chlorate, but the production of sodium hypochlorite uses the same raw materials and production technology as sodium chlorate.

References: I-18 and I-19

Source: Franklin Associates, A Division of ERG

Ozone Generation

Ozone is a disinfectant used for the HOD container washing process. Ozone is an unstable molecule and thus must be generated at the point of application (Reference I-10). Based on a discussion with a manufacturer of HOD container washing equipment (Reference I-7), the ozone generators that are integrated with HOD container washing equipment use liquid oxygen (as opposed to ambient atmospheric oxygen) to generate ozone. (Data for the production of liquid oxygen is provided in Appendix C and is not repeated here.)

Ozone generators that use liquid oxygen feed systems consist of a storage tank, evaporators to convert the oxygen liquid to a gas, filters to remove impurities, and pressure regulators to limit the gas pressure (Reference I-10). Electricity is required to convert oxygen (O_2) to ozone (O_3) as well as to circulate cooling water. Data for the production of ozone are shown in Table I-4.

Table I-4

DATA FOR THE PRODUCTION OF 1,000 LBS OF OZONE

Raw Materials		
Oxygen	1,000	lb
Process Energy		
Electricity (grid)	11,000	kwh
Environmental Emissions		
Atmospheric Emissions		
Ozone	0.10	lb

References: I-10 and I-21

Source: Franklin Associates, A Division of ERG

HOD Container Washing

When five-gallon HOD containers are unloaded at the bottle washing facility, they are inspected for unwanted liquids or solids. Bottle washers can wash between 30 and 900 bottles per hour depending on production requirements. The bottle washing process typically has four cycles: (1) wash cycle, (2) rinse cycle, (3) ozone rinse cycle, and (4) clean water rinse cycle.

HOD bottle washing facilities have bottle washing equipment that requires heated water. A bottle washing unit has a water reservoir tank with 220-volt electric heating elements that heat water from room temperature to between 120 and 150 degrees Fahrenheit (References I-7 and I-8).

Each bottle is washed by four, one-minute cycles. A chlorine-based cleansing agent, most commonly sodium hypochlorite, is used during each wash cycle (References I-7 and I-20). Some bottle washers use a dilute (2.5%) caustic solution for polycarbonate containers (polycarbonate is currently the predominant material for HOD containers) (Reference I-9). No data are available for the use rates of these cleaning agents. As an initial estimate, it will be assumed that sodium hypochlorite and caustic soda each account for one percent of the weight of water used by the HOD container washing process (Reference I-21). Sensitivity analysis on chemical use rates may be performed if chemical use for washing is shown to have a significant influence on results for HOD systems.

The rinse cycle also provides four rinses per bottle at 120 degrees to 150 degrees Fahrenheit. The ozone rinse cycle is performed at room temperature using an ozone solution (Reference I-7) with a concentration from 0.1 to 0.4 mg/L (Reference I-22). A typical HOD washing machine generates 40 to 50 gallons of ozone solution per hour, which is used to wash approximately 450 bottles. Assuming water with an ozone concentration of 0.4 mg/L, the use of 50 gallons of ozone solution per hour, and a throughput of 450 bottles per hour translates to 0.00037 pounds of ozone per 1,000 bottles.

The bottle is given a final clean water rinse to wash away any cleanser or sanitizing agent that might remain in the bottle. The net water usage for the entire bottle washing process is 1 to 1.5 liters (0.26 to 0.40 gallons) of water per bottle, as reported by a representative of an HOD washing facility (Reference I-7).

Table I-5 shows data for the washing of five-gallon HOD containers. These data include the consumption of water, cleaning agents, and disinfecting agents for the cleaning of 1,000 5-gallon containers, as well as the energy required to heat the water used for the washing process. Energy for water heating was calculated based on the *net* water inputs to the process reported for HOD washing so that there is no double-counting of heating energy requirements for hot wash or rinse water that is recirculated in the washing process.

Table I-5

DATA FOR THE WASHING OF
1,000 5-GALLON REUSABLE CONTAINERS (1)

Raw Materials		
5-gallon HOD containers	1,000	count
Water (from municipal water treatment source)	330	gal
Sodium hydroxide (1)	0.083	lbs
Sodium hypochlorite (2)	3.30	lbs
Ozone (3)	3.7E-04	lbs
Energy Usage		
Process Energy		
Electricity	71	kwh

(1) A 2.5% solution of sodium hydroxide solution is used as a cleaning agent. Franklin Associates estimates that it accounts for 1% of the weight of water used for washing bottles.

(2) Sodium hypochlorite is as a cleaning agent. Franklin Associates estimates that it accounts for 1% of the weight of water used for washing bottles.

(3) An ozone solution of up to 0.4 mg/liter is used for disinfecting bottles. Typical HOD washing equipment uses 50 gallons of ozone solution per hour and washes 450 bottles per hour.

(4) HOD washing equipment includes a water heater supplied by electric current. This data assumes a 90% efficiency in converting electrical energy to thermal energy, and a temperature increase from 58 to 130 degrees Fahrenheit.

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Source: Franklin Associates, A Division of ERG

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APPENDIX J

WASTE MANAGEMENT

INTRODUCTION

This appendix discusses the waste management options for postconsumer containers and associated packaging materials, including landfilling, combustion with and without energy recovery, recycling, and composting. This appendix also discusses the management of waste water, which results from washing single serving re-usable containers in residential dishwashers and large reusable containers by HOD (home and office delivery) bottlers.

Packaging that is not reused or recycled by consumers typically becomes part of the managed municipal solid waste stream. It is recognized that some small fraction of postconsumer packaging may be burned by consumers (particularly in rural areas) or littered; however, no data exist to quantify these amounts or their impacts with any degree of confidence. Thus, disposal of postconsumer packaging by on-site burning or littering is not included in this analysis. This analysis considers only landfilling and large-scale combustion as management options for postconsumer packaging.

LANDFILLING

Approximately 93 percent of all discarded municipal solid waste in Oregon that is not diverted for reuse, recycling, or composting is currently being landfilled (Reference J-28). The energy requirements for landfilling operations include the energy required to collect and transport solid waste to the landfill and to run the compacting equipment at the landfill.

The energy to collect and transport materials to a landfill or transfer station using a packer truck is derived by converting the weight of each material to the volume it occupies in the packer truck and multiplying the volume by the average fuel use per truckload. The packer truck densities used in this study are reported in Table J-1. A typical packer truck has a 25-cubic-yard volume and generally achieves a volume utilization of 80 percent. Packer trucks are assumed to use approximately 10.4 gallons of diesel per load (Reference J-2) on average, although actual fuel use will depend on the mode of transportation and distance to landfill, which can vary widely between communities. A route distance of 25 miles is used in this analysis. The amount of diesel fuel allocated to transport postconsumer solid waste by a packer truck on-route is calculated by the following equation:

$$\frac{\textit{Weight of discards}}{\textit{Packer truck density of discards}} \times \frac{\textit{10.4 gallons diesel}}{\textit{25 yd}^3 \times 0.8} \qquad \text{(Equation J-1)}$$

At the end of the route, Oregon waste is transported an average estimated distance of 67 miles to a disposal site, with 10 percent of the transport by rail and 90 percent by truck (Reference J-28).

The diesel fuel requirements for the operation of landfill equipment are calculated using Equation 2.

$$\frac{\textit{Weight of discards}}{\textit{Landfill density of discards}} \times \frac{\textit{500 gallons diesel}}{\textit{2,667 yd}^3} \qquad \text{(Equation J-2)}$$

The materials buried in the landfill are reported in the analysis as postconsumer solid waste. The landfill density factors shown in Table J-1 are used to convert the weight of the discarded materials to the volume they occupy in the landfill. These factors are based on landfill samples and compaction tests.

Table J-1

PACKER TRUCK AND LANDFILL DENSITY FOR MATERIALS

	Packer truck density (lb/cubic yard)	Landfill density (lb/cubic yard)
PET bottle	295	355
PLA bottle	295	355
Polypropylene closure	295	355
Reusable plastic containers	295	355
Reusable steel containers	496	557
Reusable aluminum containers	449	250
Glass bottle or drinking glass	2360	2800
Plastic film	500	667
Corrugated paperboard	664	819

References: J-3 and J-4.

Source: Franklin Associates, A Division of ERG

Decomposition of paperboard packaging (specifically, corrugated paperboard) was modeled based on the cumulative amount that would be released over time if there were complete decomposition of the carbon in the cellulose and hemicellulose fractions of the material (calculated from information in Reference J-11). The composition of landfill gas as generated is approximately 50 percent by volume methane and 50 percent by volume CO_2.

Although PLA resin is derived from biomass, NatureWorks LLC's website states that PLA in an inactive landfill (i.e., low temperature, limited moisture) would not become biologically active. However, the same reference goes on to say that PLA placed in a biologically active landfill would actively biodegrade, contributing to methane production (Reference J-24). Temperature and moisture conditions in Oregon landfills may be sufficient to support hydrolysis. Because of the uncertainty surrounding PLA degradation in landfills, the LCI model was set up to evaluate a range of decomposition scenarios for landfilled PLA containers.

It is estimated that 62 percent of methane generated from solid waste landfills in Oregon is converted to CO_2 before it is released to the environment. Twenty-one percent is flared, 37 percent is burned with energy recovery, and 4 percent is oxidized as it travels through the landfill cover (Reference J-28). Biomass CO_2 released from decomposition of paper/board (or from oxidation of biomass-derived methane to CO_2) is considered "biogenic." The CO_2 released represents a return to the environment of the carbon taken up as CO_2 during the tree's growth cycle and does not result in a net increase in atmospheric CO_2, assuming that forests that serve as sources of pulp wood are managed to maintain their overall carbon balance. Methane releases to the environment from anaerobic decomposition of biomass are not considered biogenic, however, since these higher global warming potential releases result from human intervention. As such, in the impact assessment phase of the analysis, these emissions are counted as a net contribution to global warming.

For landfill gas that is burned with energy recovery, the gross energy recovered from combustion of landfill gas was converted to displaced quantities of grid electricity using a thermal to electrical conversion efficiency of 1 kWh per 11,700 Btu, from the U.S. EPA's Landfill Methane Outreach Program (LMOP) Benefits Calculator (Reference J-30).

Although there are models (Reference J-10) that include other trace substances in landfill gas, these are associated with landfill gas produced from mixed municipal solid waste, and there is insufficient data to allocate these trace emissions to individual materials. Similarly, such models include material-specific leachate composition data based on allocations of mixed MSW leachate. These allocations are dependent on many assumptions; in addition, allocated composition data are not available for all materials of this analysis. Thus, only the emission of greenhouse gases is accounted for in the landfill modeling for this analysis.

Data for the landfilling of materials are shown in Table J-2.

Table J-2

DATA FOR THE COLLECTION AND LANDFILLING OF 1,000 POUNDS OF POSTCONSUMER MATERIALS

		PET bottle or HOD container	PLA bottle		Polypropylene closure	Polycarbonate (HOD)	Glass bottle or drinking glass	Steel reusable container	Aluminum reusable container	Plastic film	Corrugated paperboard
Material Inputs											
Pounds of material to landfill	lbs	1,000	1,000		1,000	1,000	1,000	1,000	1,000	1,000	1,000
			degree of PLA decomposition								
Decomposition characteristics			0%	100%							
Total weight % biomass C in material			50%								43%
Total weight % biomass C that decomposes	%	0	0	50%	0	0	0	0	0	0	19%
Of C that decomposes,											
% that produces methane	%	0	0	50%	0	0	0	0	0	0	50%
% of Methane released w/o treatment	%	0	0	38%	0	0	0	0	0	0	38%
% of Methane burned for energy recovery	%	0	0	37%	0	0	0	0	0	0	37%
Heating value (HHV) of methane	Btu/lb	na	na	23,930	na	na	na	na	na	na	23,930
Energy Usage											
Process Energy											
Diesel (1)	gal	0.53	0.53	0.53	0.53	0.53	0.07	0.34	0.75	0.28	0.23
Gross recovered energy from combustion of landfill gas (2)	thou Btu			(2,951)							(1,126)
Delivered electricity (2)	kwh			(252)							(96)
Transportation Energy											
Route collection in single unit truck (diesel)	gal	1.76	1.76	1.76	1.76	1.76	0.22	1.05	1.16	1.04	0.78
Transport from end of route to disposal site (67 mi)											
90% transported by truck	ton-miles	30.15	30.15	30.15	30.15	30.15	30.15	30.15	30.15	30.15	30.15
10% transported by rail	ton-miles	3.35	3.35	3.35	3.35	3.35	3.35	3.35	3.35	3.35	3.35
Environmental Emissions											
Atmospheric emissions											
Methane (3)	lb			127							48
CO2 credit for C sequestration in landfilled biomass material	lb		(1,833)								(884)
Solid Waste	lb	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000

(1) Represents diesel fuel used to operate equipment at site of landfill.

(2) "Gross recovered energy" and "delivered electricity" represent the same energy flow; gross recovered energy expresses the total energy released from the combustion of methane while delivered electricity is the amount of useful energy recovered from the combustion of methane. The thermal to electrical efficiency for the combustion of landfill gas is approximately 29%. Avoided emissions from displacement of grid electricity are calculated in the model, based on the mix of fuels used to produce electricity used in Oregon.

(3) Represents the methane that is released from the decomposition of material and NOT recovered for flaring or energy generation.

References: Table J-1, Equations J-1 and J-2, References J-10, J-11, J-19, J-28, and J-30.

Source: Franklin Associates, A Division of ERG

COMBUSTION WITH ENERGY RECOVERY

Approximately 7 percent of disposed municipal solid waste in Oregon is burned rather than buried in a landfill (Reference J-28). Approximately 86 percent of the material burned for disposal goes to a MSW incinerator that recovers the energy released from burning the wastes, primarily to generate electricity. This analysis reports the energy content of the materials burned in MSW incinerators. The energy content of the materials evaluated in this study is based on the higher heating values (HHVs) reported for the postconsumer materials. These values are listed in Table J-3.

No data were available for transport of ash and uncombusted residues to an ash landfill. It is likely that ash landfills are co-located with incinerators or very near, so the exclusion of ash transport should have a negligible effect on results.

The carbon content of all combusted materials is assumed to be converted to CO_2. The CO_2 from combustion is classified as biomass CO_2 (carbon neutral) for paper products and PLA, and as fossil CO_2 for plastics derived from fossil fuels.

Table J-3

HIGHER HEATING VALUES AND ASH CONTENT OF MATERIALS

	Ash Content (percent)	Higher Heating Value (HHV) (Btu/lb)	Weight % of material that is carbon
PET	0%	10,144	63%
PLA	0%	8,169	50%
Polypropylene	0%	17,200	86%
Glass	100%	0	0%
Aluminum	100%	0	0%
Steel	100%	0	<1%
Polycarbonate	0%	15,900	76%
Polyethylene film	0%	19,968	86%
Corrugated paperboard	5.06%	7,047	43%

References: J-5 and J-22.

Source: Franklin Associates, A Division of ERG

For each material that combusts, an energy credit is given based on the percentage of the material that burns and the heat of combustion of that material (Reference J-22). The gross energy recovered from combustion of landfill gas from each material in each type of equipment was converted to a displaced quantity of electricity based on the efficiency for converting WTE heat to electricity, which is approximately 1 kWh per 19,120 Btu for mass burn facilities (Reference J-31). The credit for displaced electricity is shown as a **negative input of energy**. Linking the negative kWh to the corresponding

LCI datasets for production and delivery of grid electricity will calculate the avoided emissions associated with these kWh. Data for the waste-to-energy combustion of materials are shown in Table J-4.

RECYCLING

For this analysis, postconsumer plastic products and glass are assumed to be collected by curbside collection techniques using single unit diesel trucks, or dropped off at a deposit location. Curbside collection is assumed to use 3.28 gallons of diesel per 1,000 pounds to collect recyclables and transport them to a processing facility (Reference J-12). For bottles dropped off at stores under the deposit system, it is assumed that returning bottles for a deposit will not be the primary purpose of a trip, but will occur during trips made for the purpose of making purchases. Based on this assumption, no travel in personal vehicles is assigned to bottles returned for deposit.

Currently, there are uncertainties regarding the fate of PLA bottles that are collected commingled with PET bottles. PLA bottles are similar in appearance to PET bottles, and some PLA bottles are likely to end up baled with PET in facilities that do not have sufficient technology to separate PLA and PET. In sufficient quantities, PLA can cause quality problems in recycled PET. If the PLA bottles are separated from PET, the PLA containers may subsequently be landfilled, burned for energy, composted, or recycled, depending on the PLA management options available at the location where they are separated.

This analysis does not make projections about the quantities of PLA that may be collected commingled with postconsumer PET, the processes used to separate commingled plastics and the effectiveness of these separation processes, or the fate of PLA that is separated from PET prior to recycling of the PET. The recycling energy and emissions in the analysis are based on the energy requirements to transport, bale, and reprocess postconsumer PET bottles, excluding any special requirements for separation of PLA or deleterious effects from PLA that remains in the baled PET sent to reprocessors,

After commingled postconsumer plastics are sorted, they are baled for shipment to a reprocessor. Baling is done using a double ram horizontal baler that produces a 30-inch by 44-inch by 46-inch bale (References J-9 and J-13). Bales of postconsumer plastics have an average density of 25 pounds per cubic foot. The baler uses a 100 horsepower motor and has a throughput of 5 tons per hour (Reference J-14). An LPG fueled front-end loader is used to move the material from the collection truck unloading area to the baler.

Table J-4

**DATA FOR THE COLLECTION AND COMBUSTION
WITH ENERGY RECOVERY OF 1,000 POUNDS OF POSTCONSUMER MATERIALS**

		PET bottle or HOD container	PLA bottles	Polypropylene closure	Polycarbonate (HOD)	Glass bottle or drinking glass	Steel container	Aluminum container	Plastic film	Corrugated paperboard
Material Inputs										
Pounds of material to combustion	lbs	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Higher heating value	Btu/lb	10,144	8,169	17,200	15,900				19,968	7,047
Energy Usage										
Process Energy										
Gross recovered energy (1)	thou Btu	(10,144)	(8,169)	(17,200)	(15,900)				(19,968)	(7,047)
Delivered electricity (1)	kwh	(531)	(427)	(900)	(832)				(1,044)	(369)
Transportation Energy										
Route collection in single unit truck (diesel)	gal	1.76	1.76	1.76	1.76	0.22	1.05	1.16	1.04	0.78
Transport from end of route to disposal site (67 mi)										
90% transported by truck	ton-miles	30.15	30.15	30.15	30.15	30.15	30.15	30.15	30.15	30.15
10% transported by rail	ton-miles	3.35	3.35	3.35	3.35	3.35	3.35	3.35	3.35	3.35
Environmental Emissions										
Atmospheric emissions										
Fossil carbon dioxide (2)	lb	2,292		3,143	2,772				3,143	
Solid Waste (ash)	lb					1,000	1,000	1,000		50.6

(1) "Gross recovered energy" and "delivered electricity" represent the same energy flow; gross recovered energy expresses the total energy released from the combustion of a material, while delivered electricity is the amount of useful energy recovered from the combustion of material. The thermal to electrical efficiency of a WTE incinerator is approximately 18%. Avoided emissions from displacement of grid electricity are calculated in the model, based on the mix of fuels used to produce electricity used in Oregon.

(2) Represents the amount of fossil carbon dioxide that results from the combustion of material and is based on the carbon content of the material. The carbon content of biomass-derived materials (PLA, corrugated) does not produce fossil carbon dioxide.

References: Tables J-1 and J-3, Equations J-1 and J-2, References J-22, J-28, and J-31.

Source: Franklin Associates, A Division of ERG

In the mechanical recycling process for plastics, the postconsumer plastic is received at the plant, typically in bales of recyclable plastic containers. The bales are sent through a debaler and then sorted if they contain mixed plastics. Sorting is usually done by hand. The selected plastics are then sent by conveyor belt to a granulator. The granulated plastic flakes are blown into a washer. They are washed in water of approximately 200 degrees F and then spun dry. The flakes must be completely dry before going into the extruder; therefore, they may be stored to dry for an extended period of time (Reference J-9).

The dried plastic flakes are then sent through an extruder. In the extrusion process, the granules of plastic are fed into a hopper which feeds into the heated barrel of the extruder. In this barrel, the screw rotates and sends the resin to a melt reservoir. When a sufficient amount of resin is in the reservoir, the screw pushes the plastic through an exit port. The resin is then immersed in a water-filled cooling tank. It is air dried and enters the pelletizer, which cuts the rod of dried resin into small pellets. The final pellets are packed and sent to plastic product manufacturers.

Energy data for mechanical recycling of plastics is based on a survey of six different recycling plants from across the United States. As very few of the plants could tell how many kilowatt-hours of electricity they use, a survey of motor sizes for each piece of machinery and their throughput was taken. From the motor sizes, an efficiency for each size motor was found (References J-16 and J-17). The motors were assumed to be a 3-phase, 60 Hz, 1750 RPM, wound-rotor type.

Table J-5 shows the energy requirements and environmental emissions for the postconsumer collection and processing of postconsumer plastic bottles. Single-unit truck transport is for curbside collection or transport of deposit bottles from stores to central processing locations. Combination truck and ocean transport is based on transportation of recovered material to China for reprocessing (Reference J-29). Electricity use for recycling in China is based on a fuel mix of 79 percent coal, 0.5 percent natural gas, 2.4 percent fuel oil, 2.1 percent nuclear, and 15.9 percent hydropower (Reference J-33), which results in 2.07 lb CO_2 equivalents per kWh for Chinese electricity, compared to 1.72 and 1.25 lb CO_2 equivalents for the U.S. and Oregon electricity grid mixes that are shown in Appendix A tables A-07a and A-07b.

It is estimated by Oregon DEQ that currently 37 percent of plastic water bottles are collected for recycling, with 30 percent successfully delivered for recycling and 7 percent ending up as industrial waste due to commingling and sorting problems. Under the bottle bill, it is estimated that 56 percent of bottles will be redeemed and recycled through the deposit system, and another 6 percent will be collected through other means. Of that 6 percent, 5 percent will end up being recycled and 1 percent disposed as industrial waste (Reference J-32).

According to DEQ, the projected rate for water bottle recovery is lower than the recovery rate for beer and soft drink containers under the deposit program because the beer and soft drink recycling rate is heavily influenced by the high recovery rate for aluminum cans that represent a large portion of the beer and soft drink containers; recovery rates are lower for plastic containers. In addition, DEQ noted that beer and soft drinks are commonly consumed at home, and containers consumed at home have a high probability to get redeemed or recycled. Bottled water is often consumed on the go, and beverages consumed on the go are much less likely to be redeemed or recycled. Therefore, DEQ believes that 62 percent is a reasonable estimate for recovery of water bottles under the deposit program.

Table J-5

DATA FOR THE CURBSIDE COLLECTION AND RECYCLING OF 1,000 POUNDS OF PLASTIC BOTTLES *

	Curbside Collection		Deposit Drop-off	
Material Inputs				
Plastic bottles	1,000	lbs	1,000	lbs
Energy Usage				
Process Energy				
Electricity	276	kwh	276	kwh
Total Process				
Transportation Energy				
Combination truck	459	ton-miles	459	ton-miles
Diesel	4.82	gal	4.82	gal
Single unit truck**	25	miles	25	ton-miles
Diesel	3.28	gal	0.56	gal
Ocean freighter	3,294	ton-miles	3,294	ton-miles
Diesel	0.66	gal	0.66	gal
Residual	5.6	gal	5.6	gal
Environmental Emissions				
Solid Waste	100	lb	100	lb

* Includes debaling, flaking, washing, and pelletizing of postconsumer plastic from curbside collection and drop-off at a deposit location, as well as transportation to China for recycling.

** Gallons of diesel fuel are calculated differently for curbside collection and recyclables dropoff. Curbside collection fuel use is based on the packer truck density of the collected material, volume of the truck, miles traveled, and gallons/mile. Gallons for transport of material collected via deposit drop-offs are calculated based on ton-miles traveled by a truck filled with deposit containers.

References: J-7, J-8 and J-27

Source: Franklin Associates, A Division of ERG

COMPOSTING

This analysis includes the composting of PLA material. According to the NatureWorks website, PLA should be composted in commercial composting facilities; backyard composting is not recommended (Reference J-24). Composting is an aerobic decomposition process that converts PLA material into a compost product and biomass carbon dioxide. Since the carbon dioxide released from composting is derived from biomass, it is carbon neutral and thus there are zero net greenhouse gas emissions from PLA composting.

Commercial compost facilities are known to have the potential of producing a variety of emissions, including methane, ammonia, nitrous oxides, VOCs, BOD, and COD. The emissions are dependent on feedstocks and operating conditions (anaerobic vs. aerobic piles, aeration, stormwater management controls, methane recovery, etc.). No data are available for the emissions resulting from composting PLA in a commercial composting facility. This study assumes that any methane produced during composting is oxidized to carbon dioxide through the outer layers of the compost piles, resulting in no methane releases to the environment. Thus, for the composting of PLA, this analysis includes only the environmental burdens associated with transporting PLA to a composting facility.

The data for the transport of PLA to a composting facility is assumed to be the same as the single-unit truck data for the transportation of PLA to a landfill as shown in Table J-2. No data are available for separation of PLA from other postconsumer plastics or packaging. The majority of PLA composting is likely to occur from dedicated "green" facilities or events that make it a point to use all compostable items so that all collected material can be sent to a composting facility without sorting.

Unlike recycling, where material must be reprocessed into resin and then refabricated into a second product, the composting step is the fabrication step for the second product, i.e., compost; thus, the burdens for composting are allocated entirely to the compost product. Because compost remains in place where it is applied and is not collected and disposed after use, the amount of material diverted from the solid waste stream for composting is assumed to be permanently diverted from landfill. EPA has estimated a "carbon storage" benefit to applying compost to carbon-depleted soils. This represents carbon in biogenic feedstocks that is converted into complex humic molecules that are resistant to decay, thus serving to store in soils carbon that previously circulated between the biosphere and the atmosphere. Estimates of carbon storage for composted PLA were not identified and are assumed to be zero.

WASTEWATER MANAGEMENT

In this analysis, wastewater treatment is defined as the activity of treating wastewater from residential dishwashers and wastewater from the washing and sterilization of 5-gallon HOD containers. Energy requirements for wastewater treatment are shown in Table J-6.

Table J-6

**DATA FOR THE TREATMENT
OF 1,000,000 GALLONS WASTEWATER**

Raw Materials			
Lime	226	lb	
Ferric Chloride	70.2	lb	
Ferrous Chloride	45.6	lb	
Hypochlorite	18.5	lb	
Alum	27.4	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity (grid)	773	kwh	7,955
Natural gas	82	cu ft	91
Distillate oil	0.36	gal	57
Total Process			8,102

References: J-6, J-24

Source: Franklin Associates, A Division of ERG

Energy

The primary data source for wastewater treatment is a survey of several hundred utilities across the country by the American Water Works Association (AWWA). The survey was originally performed for an Energy Star model, and the results used in this study were filtered by the same criteria as the EPA used. After filtering the data, the answers from 245 utilities remained. These utilities provided information on the average daily influent flow and the level of treatment, as well as how much electricity and other fuels were purchased (Reference J-6).

In order to make use of survey results from all across the country, a list of municipal wastewater treatment plans was obtained from the EPA WATERS tool, which catalogues information provided in the Clean Water Needs Survey (CWNS). According to the results, there are 213 municipal wastewater treatment plants in Oregon: 180 provide Secondary treatment (including one that performs nutrient removal), 31 provide Advanced Treatment I quality effluent, and two are Advanced Treatment II with nutrient removal. While the majority of the treatment plants within Oregon treat less wastewater (sometimes much less) than the limit of 1.5 million gallons per day (MGD) in the AWWA survey, 88 percent of the flow is to plants of this size or larger.

To estimate the amount of energy required to treat one million gallons of water at each level, the AWWA utilities were separated by treatment level. Within each treatment level, the geometric mean of energy usage was used, because the datasets appeared to be log-normal, and this approach was shown to provide the best prediction of actual energy use. The predominant fuels used by the treatment facilities were electricity, natural gas and fuel oil. Fuel use was calculated based on the average percentage of each fuel used in all treatment plants nationwide. While some plants reported the use of digester gas, this data showed far more variability and uncertainty than other data, so it was not included in the total energy values. Reported values of digester gas used ranged from < 1 to nearly 13,000 ccf per million gallons. At 600 Btu per cubic foot, the energy from reported digester gas use would be greater than all other energy sources combined. Because of the uncertainty surrounding the digester gas data, emissions from the combustion of digester gas have not been included.

Another reason for excluding digester gas data from the analysis is because the treatment of wastewater from washing drinking containers and HOD bottles is not expected to contribute biosolids to the wastewater treatment process. If no sludges are generated, less treatment energy is required. According to Reference J-26, approximately 56 percent of energy use in a typical wastewater treatment plant is associated with the activated sludge aeration process. In Table J-6, the percentage of energy used for activated sludge aeration has been removed, since no biosolid sludge is expected to be produced from the wastewater in the system.

Chemical Usage

A wide range of chemicals can be used in the treatment of wastewater, depending on the level of treatment desired and the characteristics of the influent. For this study, an estimate of chemical usage has been based on data reported for three wastewater treatment plants (Reference J-25). While these three utilities cannot be taken as representative for all plants in Oregon, the energy for chemical production accounts for ~10 percent of the life cycle energy at all three utilities. Because it represents such a small amount of the total energy for wastewater treatment, an estimate of this type was deemed acceptable.

Treatment Processes

Wastewater flows from industries and most households to a local POTW where pollutant levels are reduced before discharge to the environment. Wastewater is treated in stages involving various treatment technologies (Reference J-26)[5].

[5] All treatment descriptions have been taken from reference J-26.

Preliminary Treatment

Pretreatment of wastewater can include a screening device, a comminutor, oil and grease separator, grit removal, and equalization and neutralization. Various pretreatment steps are required depending on the characteristics of the wastewater but, in general, pretreatment will increase the efficiency of the primary treatment and later processes.

Bar screens remove large solid material that otherwise might clog later treatment processes. Oil and grease can be removed by aeration, flotation, and skimming. When air is introduced, grease particles and large suspended solids adhere to the bubbles, float to the top, and are skimmed off.

Grit, such as sand or gravel, is removed by aeration and settling prior to any mechanical equipment so that abrasion can be kept to a minimum. A comminutor grinds up the solids that are not removed in the previous processes to promote settling in primary treatment.

Often, the flow of wastewater is equalized by use of a basin, because of the variance in the amount of influent wastewater. This basin will also neutralize the influent, as there may be occasional concentrations of contaminants or extreme pH.

Primary Treatment

After pretreatment, the wastewater enters a large rectangular or circular tank where gravity settling takes place. As the solids sink to the bottom, a rotating belt device pushes them into a hopper where they can be pumped out as sludge.

Some primary treatment tanks are designed to provide top layer skimming and bottom collection simultaneously. Chemicals are sometimes added to the wastewater to enhance solids removal. The chemical precipitants are used to agglomerate the tiny particles into larger particles which increases the settling rate. Primary treatment removes 25 to 40 percent of the BOD, but is designed more for suspended solids removal where 50 to 70 percent removal rates are achieved.

Secondary Treatment

Secondary treatment, subsequent to primary treatment, applies a biological treatment to the wastewater. Microorganisms, with sufficient oxygen and nutrients, will oxidize the dissolved or colloidal organic matter into carbon dioxide and water.

Secondary treatment, most commonly utilizing activated sludge and trickling filters, provides an oxygen- and nutrient-rich environment, with ample means for contact between the microbes and the wastewater. This process is much like that of an aerobic stream, but is accelerated and more controlled.

Activated Sludge. In this secondary treatment process, an activated sludge is kept in suspension by the introduction of air. The air bubbles help maintain turbulence and maximum contact, but also supply the microbes with abundant oxygen. This process produces new cell material which becomes part of the activated sludge. This material passes through to a sedimentation basin where most of it is collected as sludge for treatment and disposal, but some is returned to become part of the activated sludge.

Most activated sludge treatment processes are designed to retain the wastewater for approximately 45 minutes. This allows adequate time for adsorption by the sludge flow. It is possible to remove 80 to 95 percent of the BOD from the wastewater. An aeration process can be added to increase efficiency.

Trickling Filtration. Trickling filtration works in much the same way as the activated sludge, except the microbes are attached to a fixed bed. Using a rotary nozzle, the wastewater is sprayed over a coarse rough material (the bed or medium) supporting a biological film. As the wastewater trickles through the medium, the bacteria and other microbes assimilate and oxidize the dissolved organic material. When the bacterial film grows too large to be supported by the medium, it sloughs off and is removed in the settling basin.

The trickling process provides good performance with a minimum of skilled operator attention, but is highly temperature dependent. The treatment can achieve 65 to 85 percent removal of BOD using a rock or plastic medium.

Rotating Biological Contactors. A rotating biological contactor (RBC) operates with the same principles as the previously mentioned treatments, but differs in that the wastewater flows past the biological film which is in the form of a rotating disk. Large diameter plastic disks mounted on an axis rotate slowly through a wastewater tank 40 percent submerged. The microbes on the disks form a film or slime as the water trickles down the plastic medium. BOD removal and nitrification can be accomplished in the same tank with a decrease in the power costs. The RBC attains an 80-85 percent removal of BOD.

Lagoons and Oxidation Ponds. The oldest type of secondary treatment is use of lagoons or oxidation ponds. The ponds are classified as facultative, aerated, aerobic, or anaerobic. Retention times vary from 7 to 180 days. The depth of the pond or lagoon depends on the type and varies from 1 to 15 feet.

Advanced Wastewater (Tertiary) Treatment

Processes to further treat wastewater, primarily concentrating on the removal of phosphorus, nitrogen, heavy metals, refractory organics, and pathogens include coagulation and flocculation, filtration, ion exchange, nitrification, denitrification, membrane process, air stripping, adsorption, and chemical oxidation. Each process may be designed for removal of specific undesired wastes, but may also remove other waste efficiently.

Suspended Solids. Suspended solids removal most often involves the physical straining out of finely divided solids. Microstraining, diatomaceous earth filtration, and ultrafiltration are methods used to remove fine suspended solids.

Chemical clarification consists of four stages, coagulation, flocculation, sedimentation, and filtration. In all of the filtration procedures, it is necessary, at some point, to back-wash the filter, adding to the sludge from the subsequent treatments.

Organics. Organics are removed most efficiently in advanced treatment by activated carbon. The porous carbon, usually granules, forms a bed through which the wastewater passes. The constituents of the wastewater are adsorbed by the carbon.

Inorganics. Inorganics can be treated with ion exchange, electrodialysis, and reverse osmosis. Ion exchange works much like water softening, in that undesirable ions are exchanged for less harmful ions via an ion media, which the water passes over.

Electrodialysis demineralizes wastewater by applying a voltage to a cell containing mineralized wastewater. The anion minerals will migrate to the cathode and the cations to the anode, thus removing the minerals.

In reverse osmosis, the wastewater is placed under pressure and in contact with a membrane so that water will permeate the membrane, leaving concentrated inorganic ions, organic material, and colloids. The process is approximately 90 percent efficient.

Nitrogen. Nitrogen can be removed by raising the pH level to 10 and removing the ammonia that forms by aeration. The aeration method is called gas stripping. Nitrogen can also be removed biologically through a modified activated sludge which oxidizes organic nitrogen to nitrate. Bacteria then convert the nitrate to nitrogen gas anaerobically. Selective ion exchange will also reduce nitrogen.

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