LIFE CYCLE INVENTORY OF 16-OUNCE DISPOSABLE HOT CUPS

FINAL PEER-REVIEWED REPORT

Prepared For

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By

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Abbreviations and Acronyms

EMR	Energy of material resource
EPS	Expanded polystyrene
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization
LCA	Life cycle assessment
LCI	Life cycle inventory
LDPE	Low-density polyethylene
LF	Landfill
LFG	Landfill gas
LFGE	Landfill gas energy
LMOP	Landfill Methane Outreach Program
MGP	MicroGREEN Polymers
PC	Postconsumer
PET	Polyethylene terephthalate
PSPC	Polystyrene Packaging Council
RPET	Recycled polyethylene terephthalate
SMX	Solid-state microcellular expansion
WTE	Waste-to-energy

EXECUTIVE SUMMARY

LIFE CYCLE INVENTORY OF 16-OUNCE DISPOSABLE HOT CUP SYSTEMS

INTRODUCTION

A life cycle inventory (LCI) quantifies the energy use and environmental emissions associated with the life cycle of specific products. This study examines three disposable 16-ounce hot cup systems: recycled PET (RPET) solid-state microcellular expansion (SMX) foam cups, expanded polystyrene (EPS) foam cups, and coated paperboard cups. Corrugated boxes and plastic film sleeves used to package cups for shipment were also included.

The results presented in this report comprise the full life cycle of the cup systems, except for the transportation steps required to deliver cups from the manufacturer to the locations where they are used. The discussion of LCI results focuses on energy use, greenhouse gas (GHG) releases, and solid waste.

PURPOSE OF THE STUDY

The purposes of this study are (1) to identify and quantify the energy, solid wastes, and greenhouse gas emissions associated with the production and end-of-life management of prototype disposable 16-ounce hot cups, made of expanded RPET using the new SMX technology and (2) to benchmark the prototype RPET SMX cups against commonly used disposable cups made of EPS foam and coated paperboard. For benchmarking purposes, the EPS and coated paperboard cups in this analysis were modeled based on average weight generic cups from a publicly available peer-reviewed life cycle study conducted for the Polystyrene Packaging Council (PSPC) by Franklin Associates, Ltd.[1] The average weight products in the PSPC report are based on the weights of samples obtained in 2002 from North American manufacturers.

INTENDED USE

This study was conducted for MicroGREEN to benchmark the environmental profile of a prototype MicroGREEN Polymers (MGP) RPET SMX cup relative to other disposable hot cups in wide use. MicroGREEN intends to publish an article based on the results of this study, using the analysis as a case study to illustrate the potential for reduced environmental burdens of products made with the SMX technology and recycled content. Because MicroGREEN intends to share the results of this analysis with external

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[1] "Life Cycle Inventory of Polystyrene Foam, Bleached Paperboard, and Corrugated Paperboard Foodservice Products" conducted by Franklin Associates, Ltd. for the Polystyrene Packaging Council, March 2006. Available at the American Chemistry Council website: http://www.americanchemistry.com/s_plastics/sec_pfpg.asp?CID=1439&DID=5231

parties, a peer review of the analysis has been conducted prior to public release, in accordance with the ISO standards for Life Cycle Assessment, 14040 and 14044.[2]

The results of this study apply to the specific product weights and compositions described in this report and should not be interpreted as encompassing the full range of product weights and compositions available in the marketplace. This analysis is limited to an evaluation of energy, solid waste, and greenhouse gases and makes no claims about overall environmental superiority or equivalence for the products analyzed.

FUNCTIONAL UNIT

In order to ensure a valid basis for comparison for the product systems studied, a common functional unit is used. For this study, the functional unit is production and end-of-life management of 10,000 single-use 16-ounce hot cups and associated packaging.

SYSTEMS STUDIED

Table ES-1 shows the weights of cups and packaging for each system. In addition to the cups themselves, corrugated cup sleeves are evaluated as an optional add-on for the paperboard cup system. Because paperboard cups do not provide as much insulation as foam cups, it can be uncomfortable for consumers to hold paperboard cups containing extremely hot beverages. Thus, it is common practice for cup sleeves to be used with paperboard cups to provide additional insulation. In some cases, consumers have been observed to use nested cups (“double-cupping”) or nested cups together with a sleeve.

The RPET SMX cups are produced using a new technology in which plastic is foamed without the use of a blowing agent. In the SMX process, rolls of solid plastic film with a nonwoven mesh interleaf are saturated with carbon dioxide in a pressure vessel. The saturated material is removed from the pressure vessel and allowed to desaturate at room temperature until enough carbon dioxide has migrated out of the surface of the material to provide the desired surface properties for the intended use application. The rolls of film are then passed through a heated oven which causes the carbon dioxide remaining in the interior of the film to expand, forming a microcellular foam structure inside the film, with a solid layer at the surfaces. The expanded film is cut into blanks, which are then formed into cups. All trim scrap and manufacturing scrap are fully recyclable.

At this time, the carbon dioxide used to saturate the material escapes uncaptured during the sequence of processing steps. However, in full production mode, it is likely that systems may be put in place to capture and recycle the carbon dioxide emissions. This analysis does not include projections of future carbon dioxide capture and recycle rates or the energy requirements for operating CO_2 recovery systems.

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[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.

TABLE ES-1. CUP SYSTEM WEIGHTS

	Grams per Cup	Pounds per Case of 1,000 Cups	Pounds per 10,000 Cups
RPET SMX Cup	6.3	13.88	138.8
Film Sleeves		0.28	2.8
Corrugated Box		2.50	25.0
EPS Foam Cup	4.7	10.35	103.5
Film Sleeves		0.47	4.7
Corrugated Box		3.20	32.0
LDPE-Coated Paperboard Cup	13.3	29.33	293.3
Film Sleeves		0.25	2.5
Corrugated Box		2.20	22.0
Corrugated Cup Sleeve	5.8	12.69	126.9
Corrugated Box		0.54	5.4

Weights of the SMX cup and case packaging components for all cup systems were provided by MicroGREEN.

Weights of EPS cups, coated paperboard cups, and cup sleeves are average weights from the PSPC LCI study.

Case packaging weight for corrugated cup sleeves was calculated from the shipping weight for a full case minus the weight of sleeves in the box.

Source: Franklin Associates, A Division of ERG.

The EPS cups, coated paperboard cups, and corrugated cup sleeves are modeled based on average weight products in the published peer-reviewed PSPC LCI study.

The recycled content of the RPET SMX cup material is an important difference from the EPS and coated paperboard cups, which are made from virgin materials. In today’s market, the available sources of RPET feedstock for food-grade RPET can contain up to 100% postconsumer recycled content, but RPET with varying percentages of industrial and postconsumer recycled material such as 50% postconsumer/50% industrial scrap recycled content is more common. In this analysis, the RPET is modeled as 100% postconsumer resin, which is the view of the future for SMX cups. Results for RPET SMX cups made with a 50/50 mix of postconsumer and industrial recycled content are shown in Appendix B.

SCOPE AND BOUNDARIES

The analysis includes the following steps for each disposable cup system:

- Production of cup materials (beginning with raw material extraction or collection of postconsumer material, as applicable to each cup system)
- Manufacture of cups
- Production of corrugated cup sleeves
- Production of corrugated containers and plastic film packaging sleeves used to package cups and corrugated sleeves for shipment (for corrugated, modeling includes collection and processing of postconsumer corrugated boxes and industrial scrap as well as virgin inputs to box manufacture)
- Recycling of corrugated packaging
- Disposal of corrugated and film that are not recovered for recycling
- Disposal of cups and cup sleeves that are not recycled.

DATA SOURCES

The data and modeling parameters used in the LCI came from the following sources:

- MicroGREEN: Weights of RPET SMX cups, process data for converting RPET film into foamed SMX cup blanks, equipment operating specifications for cup converting equipment used to produce SMX and paperboard cups, weights of case packaging for each cup system.
- Peer-reviewed PSPC study on disposable foodservice products: average weights of 16-ounce EPS cups, coated paperboard cups, and corrugated cup sleeves sometimes used with paperboard cups; EPS resin production data; EPS cup manufacturing data.
- U.S. LCI Database[3]: life cycle data for upstream steps leading to EPS resin production; production of PET and LDPE resins; data for production and combustion of all fuels used for process and transportation energy.
- Franklin database: Production of corrugated packaging using industry average data for the production of the various virgin and recycled paperboard inputs to linerboard and medium, production of linerboard and medium, and box fabrication, recovery, and recycling; collection and recycling of postconsumer PET; production of film from PET and LDPE resins; production of nonwoven interleaf.
- Ecoinvent database[4]: Energy requirements for processing of carbon dioxide recovered as a byproduct of industrial processes.

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[3] U.S. LCI database. Accessible to the public at www.nrel.gov/lci.

[4] Swiss Centre for Life Cycle Inventories. Database available at http://ecoinvent.com/ (license required).

The LCI results also include estimates of carbon dioxide from WTE combustion of materials, methane from decomposition of landfilled paperboard, emission credits for avoided grid electricity displaced by electricity generated from WTE energy and landfill gas combustion, and carbon sequestration in landfilled paperboard that does not decompose. The primary sources of information for modeling net global warming potential from landfilling and incineration were U.S. EPA reports containing information on generation and management of landfill methane[5,6], and a published article on methane generation from decomposition of materials in simulated landfill conditions.[7]

SENSITIVITY ANALYSIS

Three modeling issues that can significantly influence the cup system results and comparisons include the following:

- The methodology used to model the effects of recycled content and end-of-life recycling,
- The mix of fuels used for bleached paperboard production,
- The degree of paperboard decomposition in landfills.

The Executive Summary contains results for each system using two different recycling methodologies acceptable under the ISO standards. The figures in this chapter also present results for potential recycling of RPET SMX cups. Chapter 2 of this report presents results of sensitivity analyses for variations in bleached paperboard production and end-of-life paperboard decomposition.

Recycling Modeling Approach

The RPET SMX cup is made from recycled material, which is an important differentiation from the EPS and coated paperboard cups, which are made from virgin materials. As described in the **Recycling Methodology** section of Chapter 1, two approaches are used in this report for modeling the effects of recycled content and end-of-life recycling. Both of these methodological approaches are acceptable under the ISO standards; however, there are differences in the results obtained by using the two approaches.

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[5] U.S. EPA. **Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks.** Third Edition. September 2006.

[6] 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.

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

In the method referred to here as the “Postconsumer free” or “PC free” method, postconsumer material comes into its second use free of virgin material production burdens. At the end of the product’s useful life, all the burdens for disposal are allocated to the current system, unless the product is again recovered for recycling. For product that is recycled at end of life, the burdens for ultimate disposal of the material leave the system boundaries with the material as it goes on into its next use.

In the allocated open-loop recycling approach, the burdens for virgin material production, recycling, and ultimate disposal of recycled material are shared among all the sequential useful lives of the material.

Potential for RPET SMX Cup Recycling

The cups in this analysis are disposable cups, intended for a single use. There is currently very little postconsumer recycling of disposable foodservice cups due to a number of factors, including food contamination problems, need to separate cups from other materials in mixed-material foodservice waste streams, and lack of a widespread infrastructure for recycling of disposable foodservice products made of EPS and coated paperboard. For EPS cups, the low density of the material presents additional difficulties in cost-effectively transporting collected material to a reprocessing location. For coated paperboard cups, the coating must be separated from the fiber before the paperboard can be recycled. While there have been some pilot programs for recycling foodservice items, these have tended to be linked to operations generating large volumes of specific types of postconsumer material (i.e., so that material sorting and transportation requirements are minimized).

The RPET SMX cup has some advantages for potential recycling compared to the EPS and coated paperboard cups. The SMX cup is thinner and more flexible than EPS, so the SMX cups will compact more efficiently for transportation. The SMX cup has no coatings or additives that would complicate recycling processes, and it is made from PET, a material for which there is an established recycling infrastructure.

There are still challenges to be overcome, however. Because RPET SMX cups look like paperboard cups, recycling personnel seeing these cups in a mixed waste stream would almost certainly identify them as paperboard and remove them from the PET recycling stream. Thus, the cups would need to be marked in some way so that they could readily be identified as PET, and recycling personnel would need to be trained to identify them. However, this problem could be minimized if a coffee shop, cafeteria, or other venue were to use *only* RPET SMX cups, so that recovered cups could be delivered directly to a recycler without requiring additional sorting.

The figures in this chapter include results for an RPET SMX cup postconsumer recycling scenario illustrating the potential reduction in environmental burdens for the RPET SMX cups if they were used in an application where they would be recovered and recycled.

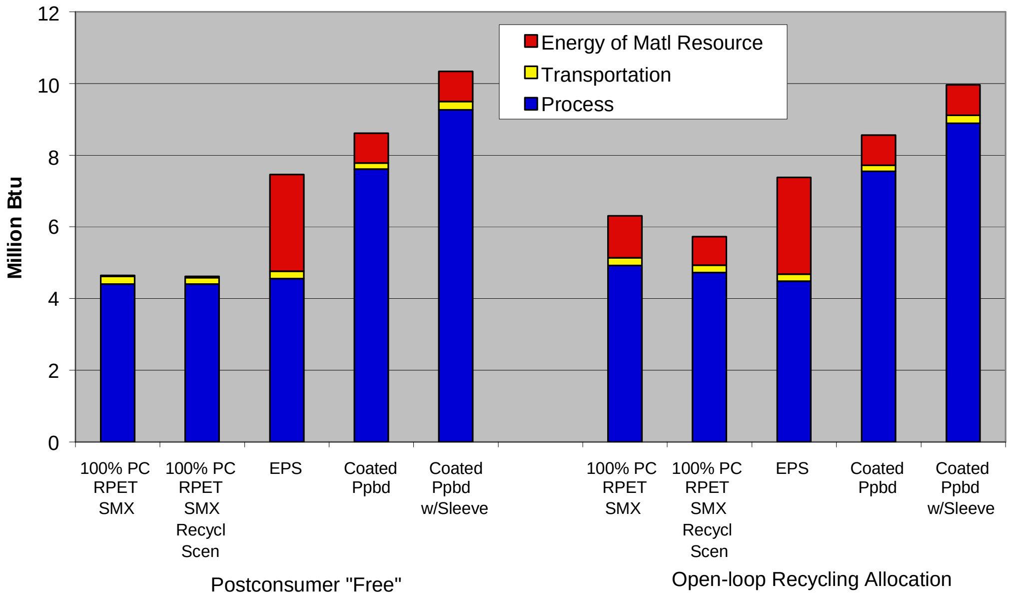
LCI RESULTS

The following sections describe the categories used for reporting results for each cup system. Each results figure in this chapter presents one set of results based on the "PC free" recycling methodology, and a second set of results based on the shared open-loop allocation recycling methodology. When comparing results for these two recycling methodologies, results for the PC free method have lower material production burdens and higher disposal burdens compared to the open-loop allocated approach, in which the production and disposal burdens are shared between all the useful lives of the material. **Observations and conclusions based on the LCI results are summarized at the end of this chapter.**

Energy Results

Figure ES-1 show energy results for three categories: process energy, transportation energy, and energy of material resource. **Process energy** includes energy requirements for all processes used to extract, transform, fabricate, or otherwise effect changes on cup materials or packaging materials throughout their life cycle. **Transportation energy** is the energy used to move materials and products from location to location during the journey from raw material through end of life. **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 the plastic resins used in cups and film packaging sleeves.

Figure ES-1. Total Energy by Category for 10,000 Cups and Packaging



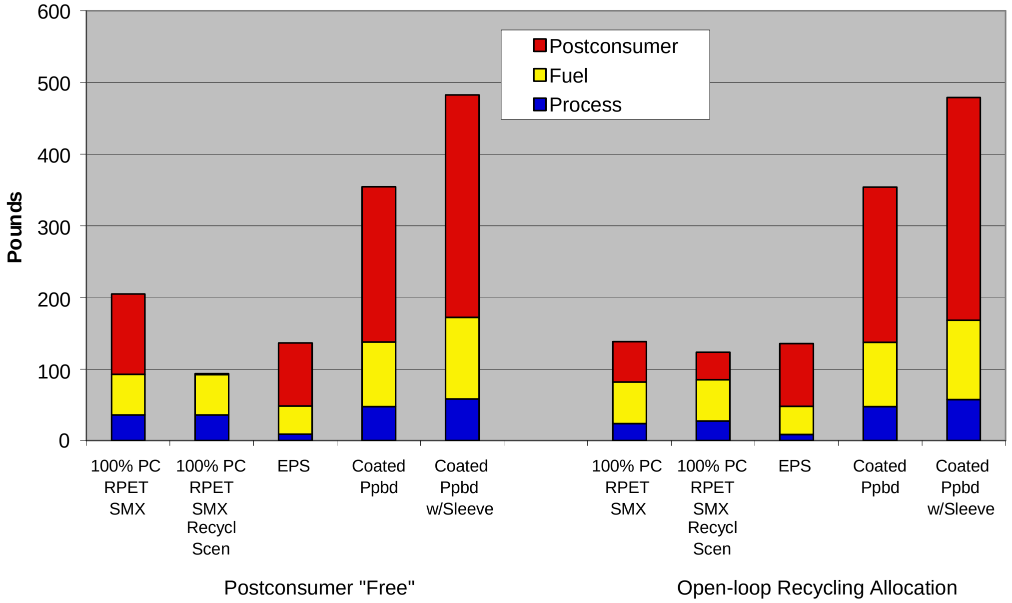
For total energy, a percent difference of 10% or greater between 2 systems' results is considered significant.

Solid Waste

Solid wastes are broadly categorized into process wastes, fuel-related wastes, and postconsumer wastes. **Process wastes** are the solid wastes generated by the various processes used to extract, transform, fabricate, or otherwise effect changes on materials and products throughout their life cycle. **Fuel-related wastes** are the wastes from the production and combustion of fuels used for process energy and transportation energy. **Postconsumer wastes** include postconsumer cups that are landfilled, as well as ash from municipal waste combustion of 20 percent of the postconsumer cups and packaging that are disposed.

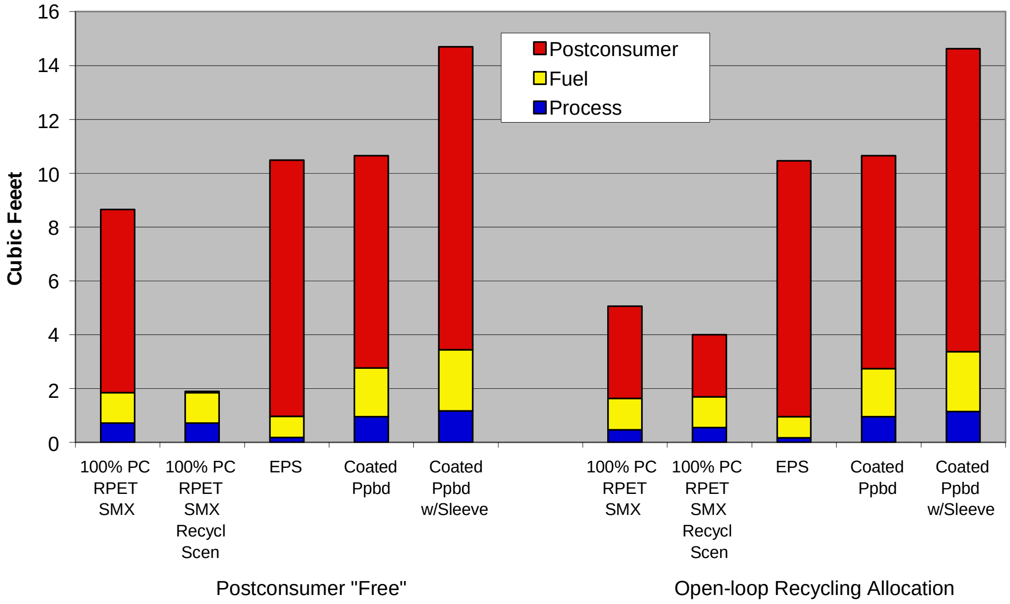
Solid waste results for each system are shown in Figure ES-2 for solid waste by weight and Figure ES-3 for solid waste by volume. The weights of postconsumer cups and packaging shown in Figure ES-2 are divided by their landfill densities to convert them to the postconsumer volumes shown in Figure ES-3. Because the foam cups have a lower density than the paperboard cups, the cups occupy a large amount of space relative to their weight. As a result, the large differences in **weight** of postconsumer solid waste for the different cups become much smaller differences when expressed on a **volume** basis.

Figure ES-2. Total Weight of Solid Waste by Category for 10,000 Cups and Packaging



For solid waste, a percent difference of 25% or greater between 2 systems' overall results is considered significant. For the weight of postconsumer solid waste only, a percent difference of 10% is considered significant.

Figure ES-3. Total Solid Waste Volume by Category for 10,000 Cups and Packaging



For volume of solid waste, a percent difference of 25% or greater between 2 systems' overall results is considered significant.

Global Warming Potential

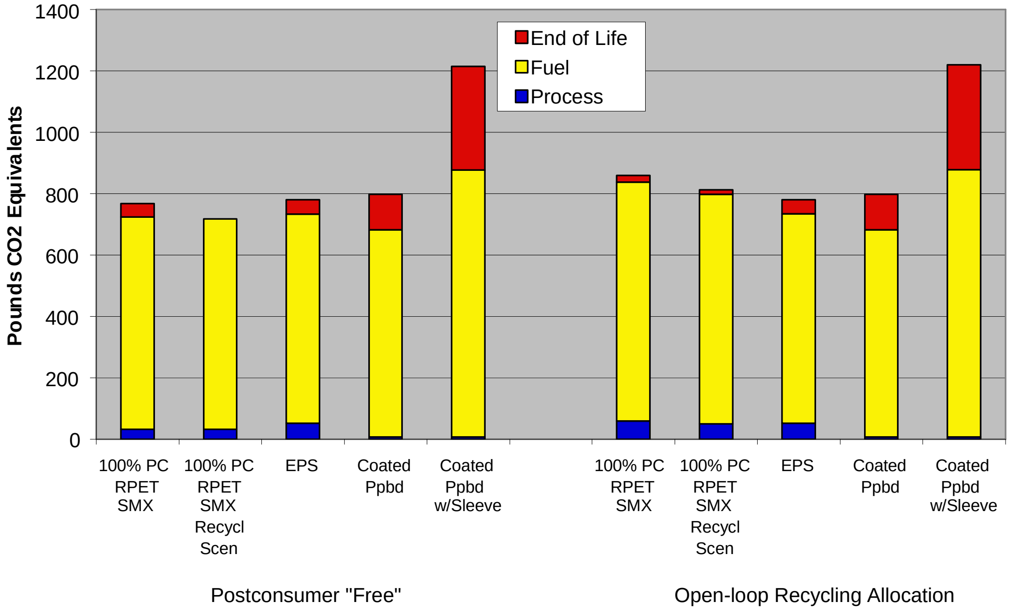
In this LCI, the evaluation of emissions is limited to greenhouse gas emissions and their global warming potential. Greenhouse gas emissions include emissions released directly from **processes** (e.g., fugitive methane emissions from natural gas extraction and processing, emissions from chemical reactions, releases of carbon dioxide used in the SMX expansion process) and those associated with the combustion of **fuels** used for process and transportation energy. The analysis also includes estimates of the greenhouse gas emissions resulting from **end-of-life** management of packaging system components. The end-of-life estimates are more uncertain than process and fuel-related emissions because the end-of-life estimates include projections and assumptions about the decomposition of paperboard in landfills and the management of landfill gas, which can vary greatly depending on conditions at individual landfills.

The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. Because different greenhouse gases have different global warming "potencies", global warming potential (GWP) factors are used to normalize emissions of different substances to a common basis of carbon dioxide equivalents. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide, which is assigned a GWP of 1. The weight of each GHG emission is multiplied by its GWP, then the carbon dioxide equivalents are summed.

For paperboard cups and corrugated packaging, carbon dioxide emissions from the use of wood-derived energy in paperboard mills are considered part of the natural carbon cycle and are not included in the GHG totals as a net contribution to atmospheric carbon dioxide. Similarly, carbon dioxide emissions from WTE combustion of paper products are also considered carbon neutral, since they return the carbon content of the material to the atmosphere in the same form in which it was taken up during the tree's growth cycle.

Figure ES-4 shows total greenhouse gas emissions by category for each cup system. The end-of-life GWP for paperboard items in Figure ES-4 represents a scenario in which the degree of decomposition for paperboard products was 50 percent of the maximum degree of decomposition in landfill simulation experiments, and landfill gas management was based on the national average composite scenario.

Figure ES-4. Total Global Warming Potential by Category for 10,000 Cups and Packaging



For GWP, a percent difference of 25% or greater between 2 systems' overall results is considered significant.

OBSERVATIONS AND CONCLUSIONS

In the following summary, the minimum percent difference between two systems' results for the difference to be considered significant is 10% for energy results and weight of postconsumer solid waste, and 25% for weight of process and fuel-related solid wastes, volume of solid waste, and GWP.

- **Recycled Content.** An important differentiating factor between the RPET SMX cup and the EPS and paperboard cups is the use of postconsumer resin in the SMX cup. The other cups are produced from virgin materials. Results in the Executive Summary and the main report represent RPET with 100% postconsumer content. It is more typical for RPET film in the current market to contain some mix of postconsumer and postindustrial recycled content. Results for cups made from RPET with 50% postconsumer content and 50% postindustrial content are presented in Appendix B. The results for 100% postconsumer RPET should be considered as the most favorable scenario for RPET SMX cups.
- **Recycling Methodology.** Different methods can be used for allocating virgin material burdens among product systems that produce and use recycled material. Two approaches were used in this analysis. Conclusions about the relative environmental profiles for RPET SMX cups and other types of cups depend in some cases upon the methodology used to assign burdens to the postconsumer resin used in the RPET SMX cup.
- **Results for No Cup Recycling**
  - **Energy.** The light weight of the RPET SMX cup and its use of 100% postconsumer recycled resin both help reduce the energy requirements for the SMX cup. Regardless of the recycling methodology used to allocate burdens for the recycled content, the RPET SMX cup system has lower total energy requirements than the other cup systems.
  - **Weight of Solid Waste.** For the PC free modeling, all the PC disposal burdens for the PET are allocated to the cup system, so the RPET SMX solid waste is significantly higher than the EPS cup system solid waste. For the open-loop recycling modeling, the PET disposal burdens are allocated between the virgin PET application and the RPET cup system, and there is no significant difference between the RPET and EPS cup systems. For both recycling methodologies, the weight of solid waste for the RPET SMX cup system is significantly lower than the paperboard cup system and the paperboard cup with sleeve.
  - **Volume of Solid Waste.** For the “PC free” scenario, there is no significant difference in the total solid waste volume for the three cup systems, although results for the paperboard cup system are significantly higher when a corrugated cup sleeve is used. For the open-loop recycling scenario, total solid waste volume for the RPET SMX cup system is significantly lower than all other systems.
  - **Global Warming Potential for Cup Production.** There is not a significant difference in process and fuel-related GWP for the three cup systems when the paperboard cup is modeled using the same mix of paperboard mill fuels used in the PSPC study. Sensitivity analysis (in Chapter 2) shows that the fuel-related emissions for the paperboard cup are strongly affected by the mix of wood-derived

    and fossil fuels used for process energy at the paperboard mill. Carbon dioxide emissions from combustion of wood wastes are considered carbon neutral, but carbon dioxide from combustion of fossil fuels adds to the net GWP. Depending on the mix of fuels used at a specific paperboard mill, the paperboard cup could have higher or lower GWP compared to the plastic foam cups.
  - **End-of-Life Global Warming Potential**. The end-of-life GWP estimates are more uncertain than process and fuel-related GWP calculations because the end-of-life GWP estimates include projections and assumptions about the decomposition of paperboard in landfills and the management of landfill gas, which can vary greatly depending on conditions at individual landfills. For a 50 percent decomposition scenario with national average management of landfill gas, there was no significant difference in total life cycle GWP for the three cup systems; however, with the addition of the decomposition emissions for the cups and sleeves, the total GWP for the paperboard cup with sleeve had significantly higher results than the cup systems without sleeves.
- **RPET SMX Cup Recycling.** RPET SMX cups have characteristics that make them a good potential candidate for postconsumer recycling. Postconsumer recycling of SMX cups would further reduce their environmental profile compared to the environmental profile for cups that are disposed after use. The reduction is most significant for the solid waste results, particularly when the PC free methodology is used.
- **RPET SMX Improvement Opportunities.** In the sequence of processes used to convert RPET film to SMX cups, the cup converting process uses the most energy and has the highest greenhouse gas emissions (associated with the electricity used). The next most energy-intensive process is the saturation process. The direct process emissions of carbon dioxide released from the saturation and desaturation processes are small in comparison to fuel-related greenhouse gas emissions. Because process scrap is recycled, there is very little solid waste from the SMX cup process steps other than fuel-related waste. The greatest amount of process solid waste from the SMX system is associated with collection and reprocessing of postconsumer PET used in the RPET film, which was modeled based on single-stream curbside collection of recyclables.

CHAPTER 1

LIFE CYCLE METHODOLOGY

OVERVIEW

The life cycle inventory presented in this study quantifies the total energy requirements, solid waste, and global warming potential resulting from the production, packaging, and disposal of single-use 16-ounce hot drink cups made from several materials, including recycled PET (RPET) film foamed using the MicroGREEN solid-state microcellular expansion (SMX) process, EPS foam, and LDPE-coated paperboard.

With the exception of global warming potential, this analysis is limited to a life cycle inventory (LCI). The scope of the analysis does not include a comprehensive inventory of atmospheric and waterborne emissions, nor does the analysis attempt to determine the fate of such emissions or the relative risk to humans or to the environment due to all emissions from the systems. No judgments are made as to the merit of obtaining natural resources from various sources, for example, whether it is preferable to produce packaging from fuel resources (petroleum-derived plastics) or renewable resources (paperboard).

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.

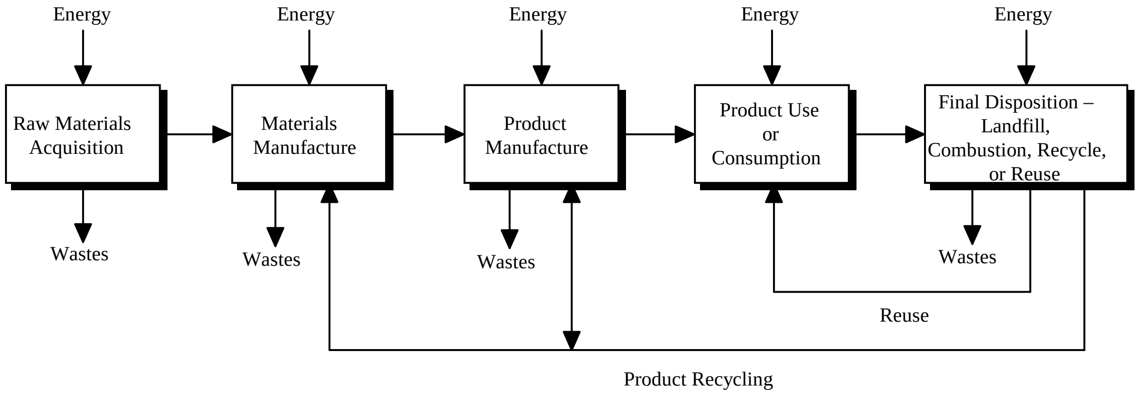


Figure 1-1. General materials flow for "cradle-to-grave" analysis of a product system.

LIFE CYCLE INVENTORY METHODOLOGY

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

Because of large uncertainties about the emissions resulting from WTE combustion of postconsumer materials in municipal waste incinerators and from decomposition of coated and uncoated paperboard material in landfills, estimated greenhouse gas emissions for end-of-life management are shown separately in the results tables. For WTE combustion of cups and packaging 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**.

The basic LCI methodology is described in the ISO standards 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.

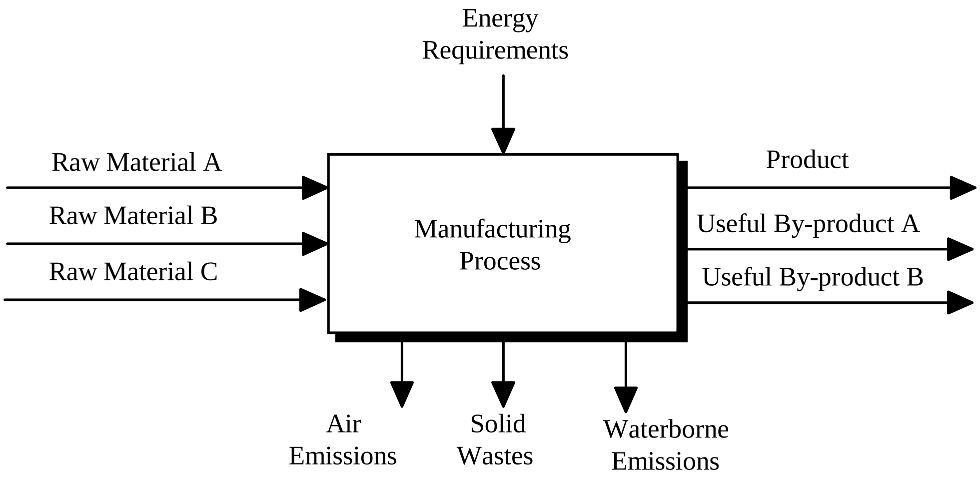


Figure 1-2. "Black box" concept for developing LCI data.

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 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 included in the scope of the study and for the energy content of materials that are produced using fossil fuel resources as material inputs. Energy results for the cup 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 an LCI because it is widely recognized that various substances emitted to the air and water differ greatly in their effect on the environment.

As noted earlier, the scope of the emissions analysis in this study is limited to greenhouse gases; however, the following sections provide a description of other atmospheric and waterborne emissions that are tracked in life cycle models.

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 unit process, there may be atmospheric emissions released directly from the process itself, as well as atmospheric emissions associated with the combustion of fuel for process or transportation energy. The amounts reported in the inventory 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 in this study focus 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. Solid wastes include industrial process- and fuel-related wastes, as well as the wastes resulting from end-of-life management of the product system being studied. Examples of industrial process wastes are residues 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, as published in ISO standards 14040 and 14044. However, for some specific aspects of life cycle inventory, there is some minor variation in 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”[8] or “partitioning”[9].

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 in the cup systems and packaging.

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 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 used in the cups and packaging, 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.)

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[8] 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.

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

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.

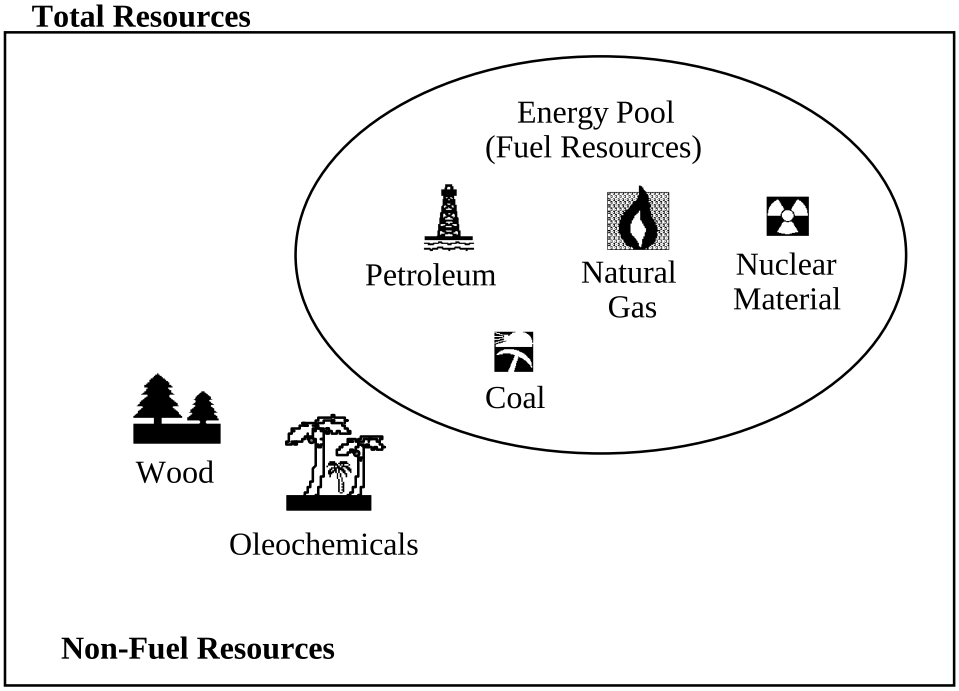

Figure 1-3. Illustration of the Energy of Material Resource Concept.

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. 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 paperboard cups and packaging that is not recycled, even though no energy of material resource is included for wood or wood-derived paperboard products under the energy of material resource accounting methodology described here.

Recycling Methodology

In this analysis, the RPET SMX cups are modeled as being produced from 100% postconsumer recycled resin. Corrugated boxes used to package cups for shipment also contain postconsumer recycled content and are recovered and recycled at end of life. When material is used in one system and subsequently recovered, reprocessed, and used in another application, there are different methods for modeling the effects of recycled content and end-of-life recycling. Material production 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 results, particularly for the RPET cup, both recycling approaches are modeled in this analysis. The methodologies are described below, and flow diagrams illustrating the methodologies are provided in Appendix C.

The simplest postconsumer recycling methodology is to allocate all virgin material burdens to the first product system using the material. At the end of the product’s useful life, no disposal burdens are allocated to product that is recovered for recycling; the disposal burdens leave the system boundaries with the material as it goes on to be recycled for its next use. Under this approach, the environmental burdens for the RPET film begin with collection of postconsumer PET material. Postconsumer recycled material comes into its subsequent use free of virgin material production burdens, so this approach is referred to in this report as the “postconsumer free” approach, or “PC free” for short.

The allocated recycling approach is more complicated. In this approach, burdens for the production and disposal of recycled material are allocated among the useful lives of the material based on the percentages of open-loop and closed-loop recycling of the material.

Open-loop recycling describes a system in which material is recovered and recycled a limited number of times before it is disposed. The most common scenario is a product that is recovered and recycled into a second product that is then disposed at the end of its life, for a total of two useful lives of the material. Material production, collection, reprocessing, and disposal burdens are allocated between the two useful lives of the material. Using this approach, burdens for virgin PET production, postconsumer PET recycling, and disposal are divided between the use of PET in its first application and its use in the RPET SMX cup, so that each useful life of the material gets half of the burdens. (For a scenario in which RPET cups are recovered and recycled, the material would have three total uses, so that the RPET cup would be assigned one-third of the burdens.)

Some materials are recycled in closed-loop systems. A true closed-loop system is one in which material is used to manufacture a product, then the product is recovered at the end of its life and recycled back into the same product, with the cycle repeating over and over again. When a material is recycled over and over again, the share of virgin material production and disposal burdens allocated to any single use of the material becomes very small, and the dominant burdens are for postconsumer collection, reprocessing, and fabrication. In the case of corrugated packaging, a significant portion of the material content of the box is derived from old corrugated containers. This recycled content is modeled as closed-loop recycling. However, because paper fibers become shorter with repeated recycling, there is a limit to the number of “closed-loop” use cycles for paper recycling. The inputs to corrugated production reflect the amount of material required for the quantity of corrugated output, taking into account the fiber losses from use of recycled content.

Open-loop and closed-loop modeling of postconsumer corrugated containers in this analysis is based on U.S. paperboard industry statistics on the postconsumer and industrial recycled content of the grades used in corrugated medium and linerboard and the recovery rate for corrugated containers in municipal solid waste.[10,11,12] Based on these statistics, the average postconsumer recycled content of corrugated is about 39 percent.

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[10] **Paper, Paperboard, and Wood Pulp**. A publication of the American Forest & Paper Association (AF&PA) Vol. 85, No. 3. March, 2007.

[11] **Paper, Paperboard, Pulp Capacity. 47th Annual Survey 2006-2009.** A publication of the American Forest & Paper Association (AF&PA). Table 7. 2007.

[12] Yield loss and kraft clippings input estimated by Franklin Associates based on industry sources. 2007.

The national recovery rate for corrugated containers is now over 70 percent overall in the U.S.[13] However, most large corrugated shipping cases of cups are probably emptied and disposed at stores or other commercial or institutional locations where corrugated is likely to be recycled; therefore, a 95 percent recycling rate for corrugated is used in this analysis. Since the recovery rate is greater than the closed-loop recycled content of the corrugated, the excess recovered corrugated is modeled as open-loop recycling.

It should be noted that the recycling methodologies described above are used for *postconsumer* material (i.e., material that has had a useful life in a product). In the case of *postindustrial* (preconsumer) scrap, the material has not yet been used in a completed product with a useful life, so all material production burdens for industrial scrap are allocated to the product that uses the scrap as input. In the case of RPET with 50% postconsumer content and 50% postindustrial recycled content, recycling allocations are applied only to the burdens for the postconsumer content; the cup system carries full burdens for industrial scrap content. Results for RPET cups with 50% postconsumer/50% postindustrial content are presented in Appendix B.

A summary of the allocations applied in this LCI is provided in Table 1-1.

Table 1-1. Allocations in Inventory of Hot Cup Systems

Process Requiring Allocation	Allocation Method	Systems Affected
Crude oil refining: Allocation of burdens among refinery outputs	Burdens allocated to total output of refinery products using mass allocation.	All cup systems, since all use petroleum-derived resins. Small effect on paperboard cup system compared to plastic cup systems, since paperboard cup only has a small weight percent of resin
Paperboard and RPET cup production: Allocation of material input burdens between cups and industrial scrap from cup blanks	All burdens for production of material that ends up in converting scrap are allocated to the scrap that is sold for external recycling	Paperboard cup, paperboard cup with sleeve, RPET cup. (Note: Unlike the paperboard and RPET cups that are produced from cup blanks, there is typically little converting scrap from EPS cup molding, and scrap is commonly reground and recycled back into the molding process rather than sold externally)
RPET SMX cup production and recycling: Allocation of postconsumer recycled resin production and disposal burdens	Two methods evaluated separately: (1) PC free: postconsumer recycled content comes in free of virgin production burdens but assigned full burdens for material recovery and reprocessing, (2) Open-loop: virgin material production burdens, recovery and reprocessing burdens, and disposal burdens divided equally among all useful lives of the material	RPET SMX cup only; other cups are produced from virgin materials and are not evaluated as being recycled after use.
Corrugated box recycled content and recycling	Industrial converting scrap assigned full material production burdens, postconsumer material evaluated using the PC free and open-loop approaches	All cup systems, since all use corrugated packaging.

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[13] U.S. EPA. Municipal Solid Waste in the United States, 2006 Facts and Figures. 2006 MSW Data Characterization Tables, Table 21, Recovery of Products in Municipal Solid Waste, 1960 to 2006 (with Details on Containers and Packaging). Accessed August 2008 at http://www.epa.gov/epawaste/nonhaz/municipal/msw99.htm .

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. In this study, MicroGREEN provided data on all processing steps required to convert RPET film into RPET SMX cups.

Confidentiality. When potentially sensitive data are provided by individual companies or organizations, Franklin Associates takes care to protect the confidentiality of the data. While the data are modeled at the unit process level in Franklin's life cycle models, a common practice for protecting confidential data is to show results only in aggregated form, after they have been compiled with two or more additional data sets so that individual data sets cannot be backed out of the averaged data.

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. The goal of this study was to benchmark the environmental profile of prototype disposable 16-ounce hot cups made of RPET SMX foam relative to 16-ounce EPS foam cups and coated paperboard cups. To minimize the time and effort required to model the EPS and paperboard cups, this study utilizes cup weights and some process data from a peer-reviewed life cycle study conducted by Franklin Associates for the Polystyrene Packaging Council.[14] These models were updated using the most up-to-date and representative data available for the U.S. from the U.S. Life Cycle Inventory database[15] and Franklin Associates' private life cycle database. Franklin's 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.

MicroGREEN provided data on all processing steps required to convert RPET film into RPET SMX cups. RPET SMX cups are not yet in full-scale production, but cup manufacturing is done on paperboard cup converting equipment. According to a representative of the cup machine company, there is no significant different in energy usage when forming SMX cups and paperboard cups on the cup manufacturing equipment.[16] The same converting energy per 10,000 cups, calculated from the cup converting equipment specifications, is used for both SMX and paperboard cups in this study.

MicroGREEN's supplier of the food-grade carbon dioxide used in the SMX process reported that the carbon dioxide is a byproduct recovered from industrial facilities such as refineries or fertilizer plants; however, the supplier declined to provide data on the energy requirements for carbon dioxide recovery and processing. Thus, carbon dioxide processing data from the Ecoinvent database were used in this model.[17]

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**.

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[14] Available at the American Chemistry Council website: http://www.americanchemistry.com/s_plastics/sec_pfpg.asp?CID=1439&DID=5231.

[15] U.S. LCI database. Accessible to the public at www.nrel.gov/lci.

[16] E-mail correspondence between MicroGREEN Polymers, Inc. and Paper Machinery Corporation, October 13, 2008.

[17] Swiss Centre for Life Cycle Inventories. Database available at http://ecoinvent.com/ (license required).

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.). 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 is required to produce primary fuels, which are in turn used to generate electricity, a circular loop is created. Iteration techniques are utilized to resolve this loop.

In 2003, Franklin Associates updated our 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.

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 listed include time-related coverage, geographical coverage, technology coverage, and more.

As described earlier in this chapter, the goal of this study was to benchmark a prototype disposable 16-ounce hot cup made of RPET SMX foam against average weight EPS foam cups and coated paperboard cups. Thus, the data quality goal for this study was to use data that most accurately represents each cup system for production of cup materials and cup fabrication in the U.S. The study does not evaluate the full range of EPS and coated paperboard cup weights available in the marketplace.

Detailed data on the RPET SMX cup processes was provided by MicroGREEN. Data for all process and transportation fuels and data for the production of PET and LDPE resin and the upstream steps leading to EPS resin production were taken from the U.S. LCI Database (www.nrel.gov/lci). Our corrugated packaging modeling, which is based on U.S. paperboard industry statistics, was thoroughly reviewed and updated in 2007. Other processes and materials in this study were modeled based on Franklin Associates’ LCI database or other published sources, such as the peer-reviewed PSPC foodservice study. The Ecoinvent database was used as the source of data for carbon dioxide processing energy requirements. Given the data sources available, the data used in this study are believed to provide an up-to-date and accurate representation of disposable cups and packaging materials.

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 the components of each cup system, 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. The data used in this report are believed to be the best that are currently available for the materials used in the cup systems studied.

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.

In summary, for the data sources used and for the specific methodology described in this report, the results of this report are believed to be as accurate and reasonable as possible. In the following **Methodology Issues** section, the subsection on **End of Life Management** discusses the uncertainty of the estimates of global warming potential resulting from landfilling and WTE combustion of postconsumer packaging items.

The results discussions in Chapter 2 present guidelines for considering differences between system results to be meaningful (greater than the margin of error/uncertainty of the data). Appendix A presents sample statistical calculations that support these guidelines.

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. Therefore, the United States national average fuel consumption by electrical utilities is used.

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.

End of Life Management

In the U.S., municipal solid waste (MSW) that is not recovered for recycling or composting, approximately 80 percent by weight is managed by landfilling (LF) and 20 percent by waste-to-energy (WTE) incineration.[18] Thus, the calculations of the GWP impacts for discarded cups and packaging that is not recycled are based on a scenario in which 80 percent goes to landfill and 20 percent to WTE combustion.

In this study, estimates of the end results of landfilling and WTE combustion are limited to global warming potential effects and energy recovery. There are GWP contributions from WTE combustion of postconsumer packaging and from fugitive emissions of landfill methane from decomposition of paperboard cups and corrugated packaging. There are also GWP credits for grid electricity displaced by the generation of electricity from WTE combustion of postconsumer cups and packaging, and from WTE combustion of methane recovered from decomposition of landfilled paperboard. Some carbon is also sequestered in the portion of landfilled paperboard that does not decompose. The U.S. EPA greenhouse gas accounting methodology does not assign a carbon sequestration credit to landfilling of fossil-derived materials such as plastic cups or plastic film packaging; 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]

In this study, decomposition of landfilled coated paperboard cups and corrugated packaging is modeled based on the maximum decomposition of paperboard materials in landfill simulation experiments conducted by Dr. Morton Barlaz, et al.[20] The landfill simulation experiments conducted by Dr. Barlaz analyzed decomposition of office paper, clay-coated magazine paper, newspaper, and corrugated. Plastic-coated paperboard foodservice items were not included in the simulated landfill experiments. This analysis uses experimental data on office paper to estimate decomposition of the bleached paperboard content of the coated paperboard cup. The coating on the cup interior surface may delay or significantly inhibit decomposition of the paperboard. Because of the potential effect of the plastic coating, and 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 paperboard

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[18] U.S. EPA. Municipal Solid Waste in the United States, 2006 Facts and Figures. 2006 MSW Data Characterization Tables. Calculated from Table 29: Generation, Materials Recovery, Composting, Combustion, and Discards of Municipal Solid Waste, 1960 to 2006. Accessed August 2008 at http://www.epa.gov/epawaste/nonhaz/municipal/pubs/06data.pdf

[19] U.S. EPA. **Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks.** Third Edition. September 2006. Section 1.3, subsection Carbon Stocks, Carbon Storage, and Carbon Sequestration. Page 6.

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

cups and corrugated packaging. Alternative results for modeling a lesser degree of decomposition are shown in the sensitivity analysis in Chapter 2.

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 bleached office paper is calculated as 44.1 percent by weight (42.6 percent potentially degradable carbon in the cellulose and hemicellulose fractions, 1.5 percent carbon in lignin), and 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 in a landfill: 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 office paper was 98 percent and 86 percent, respectively. In the corrugated samples, the degree of decomposition was 64 percent for the cellulose and 62 percent for the hemicellulose. Overall, 41 percent by weight of the office paper and 19 percent by weight of the corrugated degraded to produce CO_2 and methane. The remaining biomass carbon content did not degrade.

The composition of landfill gas as generated is approximately 50 percent by volume methane and 50 percent by volume CO_2. Currently, about 53 percent of methane generated from solid waste landfills is converted to CO_2 before it is released to the environment. Twenty-three percent is flared, 25 percent is burned with energy recovery, and about 5 percent is oxidized as it travels through the landfill cover.[21] 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 U.S. EPA's Landfill Methane Outreach Program (LMOP) Landfill Database[22] 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

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[21] 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.

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

decomposition of landfilled paperboard is converted to displaced quantities of grid electricity using an efficiency factor of 1 kWh generated per 11,700 Btu of LF gas burned.[23] Each system is credited with avoiding the GWP for the grid electricity displaced by the energy recovered from LF gas combustion.

For the carbon that remains fixed in the undecomposed portion of the landfilled paperboard, a sequestration credit is given for the equivalent pounds of CO_2 that the sequestered carbon could produce.

Waste-to-energy combustion of postconsumer cups and packaging is modeled using a similar approach to the landfill gas combustion credit. However, for WTE combustion, the CO_2 releases are modeled based on the **total** carbon content of the material oxidizing to CO_2. For combustion of paperboard, the CO_2 produced is considered carbon-neutral biomass CO_2, while the CO_2 from combustion of RPET, EPS, and LDPE 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[24], and a credit is given for avoiding the GWP associated with producing the equivalent amount of grid electricity.

The net end-of-life GWP for each cup system is calculated by summing the individual impacts and credits described above, based on 80 percent landfill and 20 percent WTE combustion of the postconsumer packaging components.

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 paperboard. The long time frame over which those emissions occur has implications that result in additional uncertainties for the landfill methane GWP estimates.

- In this analysis, the management of the aggregated landfill methane emissions is modeled based on **current percentages** of flaring, WTE combustion, and uncaptured releases. Over time, efforts to mitigate global warming may 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

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

[24] U.S. EPA. **Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks.** Third Edition. September 2006. 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

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 could gradually shift from a negative impact to a net credit.

- 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. Because of the lack of availability of good data on water use for raw material and intermediate unit processes, Franklin Associates' LCI database does not currently include water use.

Capital Equipment. The energy and wastes associated with the manufacture of capital equipment are not included. This includes equipment to manufacture buildings, motor vehicles, and industrial machinery. 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. The data collection form used for this project specifically requested that the data provider exclude energy use for space conditioning, or indicate if the reported energy requirements included space conditioning.

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. No pigments or other resin additives or ancillary components such as labels were included in the analysis, nor were paints, labels, or printing inks that may be applied to the cups or cup 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.

CHAPTER 2

LIFE CYCLE INVENTORY RESULTS FOR 16-OUNCE DISPOSABLE HOT CUP SYSTEMS

INTRODUCTION

A life cycle inventory (LCI) quantifies the energy use and environmental emissions associated with the life cycle of specific products. This study examines three disposable 16-ounce hot cup systems: RPET SMX foam cups, EPS foam cups, and coated paperboard cups. Corrugated boxes and plastic film sleeves used to package cups for shipment were also included.

The results presented in this report comprise the full life cycle of the cup systems, except for the transportation steps required to deliver cups from the manufacturer to the locations where they are used. The discussion of LCI results focuses on energy use, GHG releases, and solid waste.

PURPOSE OF THE STUDY

The purposes of this study are (1) to identify and quantify the energy, solid wastes, and greenhouse gas emissions associated with the production and end-of-life management of prototype disposable 16-ounce hot cups, made of expanded RPET using the new SMX technology and (2) to benchmark the prototype RPET SMX cups against commonly used disposable cups made of EPS foam and coated paperboard. For benchmarking purposes, the EPS and coated paperboard cups in this analysis were modeled based on average weight generic cups from a publicly available peer-reviewed life cycle study conducted for the Polystyrene Packaging Council (PSPC) by Franklin Associates, Ltd.[25] The average weight products in the PSPC report are based on the weights of samples obtained in 2002 from North American manufacturers. This analysis of RPET SMX cups and alternatives does not evaluate the full range of EPS and coated paperboard cup weights available in the marketplace.

INTENDED USE

This study was conducted for MicroGREEN to benchmark the environmental profile of a prototype MicroGREEN Polymers (MGP) RPET SMX cup relative to other disposable hot cups in wide use. MicroGREEN intends to publish an article based on the results of this study, using the analysis as a case study to illustrate the potential for reduced environmental burdens of products made with the SMX technology and recycled content. Because MicroGREEN intends to share the results of this analysis with external

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[25] "Life Cycle Inventory of Polystyrene Foam, Bleached Paperboard, and Corrugated Paperboard Foodservice Products" conducted by Franklin Associates, Ltd. for the Polystyrene Packaging Council, March 2006. Available at the American Chemistry Council website: http://www.americanchemistry.com/s_plastics/sec_pfpg.asp?CID=1439&DID=5231

parties, a peer review of the analysis has been conducted prior to public release, in accordance with the ISO standards for Life Cycle Assessment, 14040 and 14044.[26]

The results of this study apply to the specific product weights and compositions described in this report and should not be interpreted as encompassing the full range of product weights and compositions available in the marketplace. This analysis is limited to an evaluation of energy, solid waste, and greenhouse gases and makes no claims about overall environmental superiority or equivalence for the products analyzed.

FUNCTIONAL UNIT

In order to ensure a valid basis for comparison for the product systems studied, a common functional unit is used. For this study, the functional unit is production and end-of-life management of 10,000 single-use 16-ounce hot cups and associated packaging.

SYSTEMS STUDIED

Table 2-1 shows the weights of cups and packaging for each system. In addition to the cups themselves, corrugated cup sleeves are evaluated as an optional add-on for the paperboard cup system. Because paperboard cups do not provide as much insulation as foam cups, it can be uncomfortable for consumers to hold paperboard cups containing extremely hot beverages. Thus, it is common practice for cup sleeves to be used with paperboard cups to provide additional insulation. In some cases, consumers have been observed to use nested cups (“double-cupping”) or nested cups together with a sleeve.

The RPET SMX cups are produced using a new technology in which plastic is foamed without the use of a blowing agent. In the SMX process, rolls of solid plastic film with a nonwoven mesh interleaf are saturated with carbon dioxide in a pressure vessel. The saturated material is removed from the pressure vessel and allowed to desaturate at room temperature until enough carbon dioxide has migrated out of the surface of the material to provide the desired surface properties for the intended use application. The rolls of film are then passed through a heated oven which causes the carbon dioxide remaining in the interior of the film to expand, forming a microcellular foam structure inside the film, with a solid layer at the surfaces. The expanded film is cut into blanks, which are then formed into cups. All trim scrap and manufacturing scrap are fully recyclable.

At this time, the carbon dioxide used to saturate the material escapes uncaptured during the sequence of processing steps. However, in full production mode, it is likely that systems may be put in place to capture and recycle the carbon dioxide emissions. This analysis does not include projections of future carbon dioxide capture and recycle rates or the energy requirements for operating CO_2 recovery systems.

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[26] 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.

TABLE 2-1. CUP SYSTEM WEIGHTS

	Grams per Cup	Pounds per Case of 1,000 Cups	Pounds per 10,000 Cups
RPET SMX Cup	6.3	13.88	138.8
Film Sleeves		0.28	2.8
Corrugated Box		2.50	25.0
EPS Foam Cup	4.7	10.35	103.5
Film Sleeves		0.47	4.7
Corrugated Box		3.20	32.0
LDPE-Coated Paperboard Cup	13.3	29.33	293.3
Film Sleeves		0.25	2.5
Corrugated Box		2.20	22.0
Corrugated Cup Sleeve	5.8	12.69	126.9
Corrugated Box		0.54	5.4

Weights of the SMX cup and case packaging components for all cup systems were provided by MicroGREEN.
Weights of EPS cups, coated paperboard cups, and cup sleeves are average weights from the PSPC LCI study.
Case packaging weight for corrugated cup sleeves was calculated from the shipping weight for a full case minus the weight of sleeves in the box.

Source: Franklin Associates, A Division of ERG.

The EPS cups, coated paperboard cups, and corrugated cup sleeves are modeled based on average weight products in the published peer-reviewed PSPC LCI study.

The recycled content of the RPET SMX cup material is an important difference from the EPS and coated paperboard cups, which are made from virgin materials. In today's market, the available sources of RPET feedstock for food-grade RPET can contain up to 100% postconsumer recycled content, but RPET with varying percentages of industrial and postconsumer recycled material such as 50% postconsumer/50% industrial scrap recycled content is more common.[27] In this analysis, the RPET is modeled as 100% postconsumer resin, which is the view of the future for SMX cups.

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[27] Food-grade RPET with 100% postconsumer recycled content is available from Phoenix Technologies (http://www.phoenixtechnologies.net/product/default.shtml); food-grade RPET with guaranteed levels of postconsumer recycled content such as 50% or 70% can be purchased from Klockner-Pentaplast (http://www.kpfilms.com/en/products/downloadables/food/Pentafood_SmartCycle_Sales_Sheet.pdf).

Results for RPET SMX cups made with a 50/50 mix of postconsumer and industrial recycled content are shown in Appendix B.

SCOPE AND BOUNDARIES

The analysis includes the following steps for each disposable cup system:

- Production of cup materials (beginning with raw material extraction or collection of postconsumer material, as applicable to each cup system)
- Manufacture of cups
- Production of corrugated cup sleeves
- Production of corrugated containers and plastic film packaging sleeves used to package cups and corrugated sleeves for shipment (for corrugated, modeling includes collection and processing of postconsumer corrugated boxes and industrial scrap as well as virgin inputs to box manufacture)
- Recycling of corrugated packaging
- Disposal of corrugated and film that are not recovered for recycling
- Disposal of cups and cup sleeves that are not recycled.

DATA SOURCES

The data and modeling parameters used in the LCI came from the following sources:

- MicroGREEN: Weights of RPET SMX cups, process data for converting RPET film into foamed SMX cup blanks , equipment operating specifications for cup converting equipment used to produce SMX and paperboard cups, weights of case packaging for each cup system.
- Peer-reviewed PSPC study on disposable foodservice products: average weights of 16-ounce EPS cups, coated paperboard cups, and corrugated cup sleeves sometimes used with paperboard cups; EPS resin production data; EPS cup manufacturing data.
- U.S. LCI Database[28]: life cycle data for upstream steps leading to EPS resin production; production of PET and LDPE resins; data for production and combustion of all fuels used for process and transportation energy.
- Franklin database: Production of corrugated packaging using industry average data for the production of the various virgin and recycled paperboard inputs to linerboard and medium, production of linerboard and medium, and box fabrication, recovery, and recycling; collection and recycling of postconsumer PET; production of film from PET and LDPE resins; production of nonwoven interleaf.
- Ecoinvent database[29]: Energy requirements for processing of carbon dioxide recovered as a byproduct of industrial processes

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[28] U.S. LCI database. Accessible to the public at www.nrel.gov/lci.

[29] Swiss Centre for Life Cycle Inventories. Database available at http://ecoinvent.com/ (license required).

The LCI results also include estimates of carbon dioxide from WTE combustion of materials, methane from decomposition of landfilled paperboard, emission credits for avoided grid electricity displaced by electricity generated from WTE energy and landfill gas combustion, and carbon sequestration in landfilled paperboard that does not decompose. The primary sources of information for modeling net global warming potential from landfilling and incineration were U.S. EPA reports containing information on generation and management of landfill methane[30,31], and a published article on methane generation from decomposition of materials in simulated landfill conditions.[32]

SENSITIVITY ANALYSIS

Three modeling issues that can significantly influence the cup system results and comparisons include the following:

- The methodology used to model the effects of recycled content and end-of-life recycling,
- The mix of fuels used for bleached paperboard production, and
- The degree of paperboard decomposition in landfills.

Recycling Modeling Approach

The RPET SMX cup is made from recycled material, which is an important differentiation from the EPS and coated paperboard cups, which are made from virgin materials. As described in the **Recycling Methodology** section of Chapter 1, two approaches are used in this report for modeling the effects of recycled content and end-of-life recycling. Both of these methodological approaches are acceptable under the ISO standards; however, there are differences in the results obtained by using the two approaches.

In the method referred to here as the "Postconsumer free" or "PC free" method, postconsumer material comes into its second use free of virgin material production burdens. At the end of the product's useful life, all the burdens for disposal are allocated to the current system, unless the product is again recovered for recycling. For product that is recycled at end of life, the burdens for ultimate disposal of the material leave the system boundaries with the material as it goes on into its next use.

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[30] U.S. EPA. **Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks.** Third Edition. September 2006.

[31] 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.

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

In the allocated open-loop recycling approach, the burdens for virgin material production, recycling, and ultimate disposal of recycled material are shared among all the sequential useful lives of the material.

When comparing results for these two recycling methodologies, results for the PC free method have lower material production burdens and higher disposal burdens compared to the open-loop allocated approach, in which the production and disposal burdens are shared between all the useful lives of the material.

Each results table and figure in this chapter presents one set of results based on the “PC free” recycling methodology, and a second set of results based on the shared open-loop allocation recycling methodology.

Paperboard Production

Currently there are no detailed, publicly available U.S. average LCI data on the production of bleached paperboard. Therefore, in this analysis the baseline environmental burdens for paperboard cups are based on the average mix of fuels used in bleached paperboard mills as modeled in the PSPC study, which was based on data sets for a limited number of paper mills. Since that study, Franklin has collected additional mill data and averaged that data in with the data sets used in the PSPC study. The data sets showed mill-to-mill variations in the types and quantities of fuels used.

Because the mix of fossil and wood-derived energy used for paperboard production can significantly affect greenhouse gas results, the Sensitivity Analysis section near the end of this chapter includes comparative results for two different fuel mixes for paperboard production, to illustrate how the paperboard cup results change as the fuel mix shifts from a mix with high utilization of wood wastes and low use of purchased fossil fuel to a mix with lower use of wood-derived energy and higher use of coal. The total energy requirements per pound of bleached paperboard are quite similar for the two averaged data sets regardless of fuel mix, but the greenhouse gas emissions vary widely depending on the fuel mix used to provide process energy at the paperboard mills.

Paperboard Decomposition in Landfills

Another area that has a large effect on greenhouse gas emissions for the paperboard cup system is the modeling of the degree of decomposition of paperboard cups that are landfilled. As described in the **End of Life Management** section of Chapter 1, one approach is to model the maximum potential degree of decomposition based on landfill simulation experiments conducted by Dr. Morton Barlaz. However, those experiments were designed to maximize decomposition. The ultimate degree of decomposition may be different in actual landfills where moisture, temperature, and other factors differ from the experimental conditions. In addition, the coating on the paperboard cups may tend to significantly inhibit decomposition. Thus, two sets of results are shown for net greenhouse gas emissions from paperboard cup decomposition in landfills: one based on maximum potential decomposition, and one based on half the maximum experimental degree of decomposition.

LCI RESULTS

Energy Results

Comparative energy results for RPET SMX foam cups, EPS foam cups, and coated paperboard cups are shown in Table 2-2. Based on the uncertainties in LCI energy data, energy differences between systems are not considered meaningful unless the percent difference between system results is greater than 10 percent. (Percent difference between systems is defined as the difference between energy totals divided by the average of the two system totals.) This minimum percent difference criterion was developed based on the experience and professional judgment of the analysts and supported by sample statistical calculations (see Appendix A). If the percent difference between two systems' results is less than 10 percent, the comparison is considered inconclusive.

Energy by Category. Table 2-2 and Figure 2-1 show energy results for three categories: process energy, transportation energy, and energy of material resource. **Process energy** includes energy requirements for all processes used to extract, transform, fabricate, or otherwise effect changes on cup materials or packaging materials throughout their life cycle. **Transportation energy** is the energy used to move materials and products from location to location during the journey from raw material through end of life. **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 the plastic resins used in cups and film packaging sleeves.

Table 2-2 and Figure 2-1 show that the majority of the energy requirements for each cup system are for process energy, used to convert raw materials into cup materials and for cup converting operations. Transportation energy requirements are small, less than 5 percent of the total. Because all of the systems use plastic resin as the primary cup material or as a cup coating, EMR accounts for a significant share of the total energy requirements for each system except for the RPET SMX "Postconsumer free" scenario, where all virgin PET burdens, including EMR, are allocated to the product system in which the virgin PET was initially used.

No energy of material resource is assigned to wood used as a material input for paperboard cups or corrugated packaging because wood's primary use in the United States is as a material input, not as a fuel resource. Wood combusted for energy (such as wood wastes and black liquor solids burned for fuel in virgin pulp and paper mills) is included in the **process** energy shown for the corrugated systems. A significant portion of the energy used at virgin paperboard mills is derived from wood wastes and black liquor, while recycled paperboard mills rely heavily on purchased energy.

For the RPET SMX cup, the material processing steps that make the largest contributions to total energy are the cup converting step and the saturation step.

Net Energy. Table 2-2 also includes an energy credit column that accounts for the energy recovered from some of the processes involved in the production of plastic resins as well as the useful energy recovered from waste-to-energy (WTE) combustion of postconsumer packaging and LF gas. As described in the End-of-Life Management section, 20 percent of U.S. municipal solid waste that is not recovered for recycling is managed by WTE combustion. In Table 2-2, the credits from WTE combustion for cups and cup packaging are shown in the individual component lines rather than the end-of-life line. The energy requirements listed for end-of-life in Table 2-2 are for waste transport and for operation of landfill equipment.

Energy credits are small for all systems. The RPET SMX system has lower energy credits compared to the EPS and paperboard cup systems. The EPS cup system has higher recovered energy from WTE combustion because the energy content of EPS is greater than the energy content of PET. The paperboard cup systems have lower energy content per pound compared to PET, but the mass of paperboard cups disposed by WTE combustion is greater, due to the heavier weight of paperboard cups.

Fossil Energy. The column “% Fossil Energy” in Table 2-2 shows the percentage of total energy for each system component that is derived from fossil fuels (oil, natural gas, and coal). This includes use of fossil fuels not only as direct process fuels, but also as fuels to generate electricity. For plastic cups, film sleeves, and the LDPE coating on paperboard cups, fossil fuel use includes use as a raw material input for plastic resin production. Table 2-2 shows that 88 percent or more of the total energy for plastic system components is from fossil fuels. Fossil fuel energy use is lowest for paperboard cups and packaging, where there is significant use of wood energy in the production of the virgin paperboard inputs.

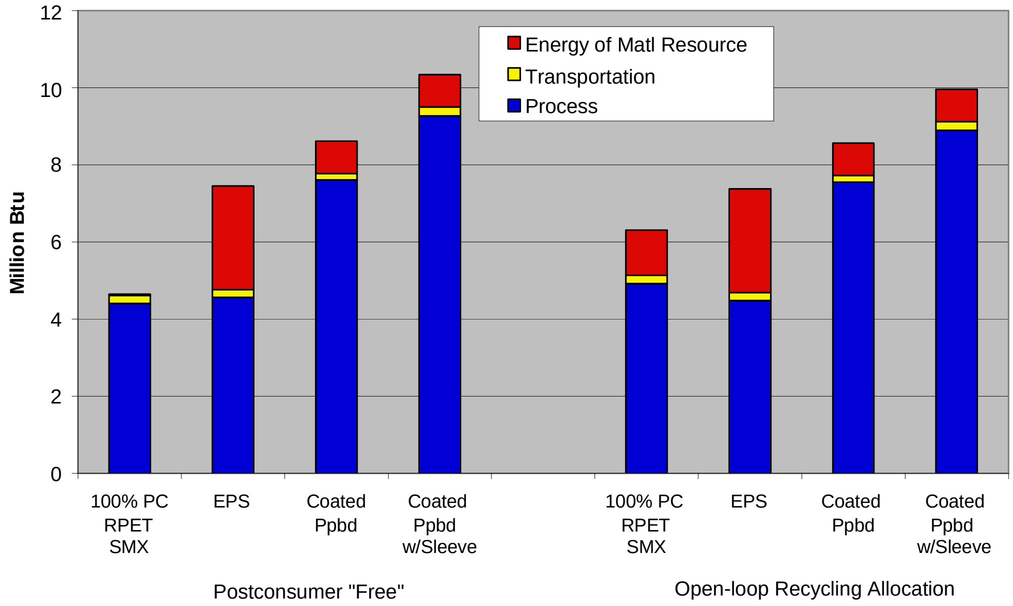
Energy by Component. The final column in Table 2-2 shows the relative energy contributions of cups and cup packaging to total energy requirements. This is also shown graphically in Figure 2-2. In every case, the cups (or cup and cup sleeve) are responsible for over 90 percent of the total energy requirements.

TABLE 2-2. TOTAL ENERGY REQUIREMENTS FOR 10,000 CUPS AND PACKAGING
(Million Btu)

	Process Energy	Transp Energy	EMR	Total Energy	Energy Credits	Net Energy	% Fossil Energy	Component % of Total	Percent Difference Between Systems	
PC FREE										
RPET SMX										
Cup	4.08	0.17	0.02	**4.28**	(0.05)	4.23	88%	92%		
Packaging	0.32	0.01	0.01	**0.34**	(0.001)	0.34	55%	7%		
End of life	0.01	0.03	0.00	**0.04**		0.04	99%	1%		
Total	4.41	0.21	0.03	**4.65**	**(0.05)**	**4.60**	**86%**	**100%**		
	95%	5%	1%							
EPS									RPET SMX	
Cup	4.08	0.14	2.58	**6.80**	(0.37)	6.43	95%	91%	compared to EPS	
Packaging	0.47	0.02	0.12	**0.61**	(0.01)	0.59	67%	8%	% Diff	% Diff
End of life	0.01	0.04	0.00	**0.05**		0.05	99%	1%	Total Energy	Net Energy
Total	4.56	0.20	2.69	**7.46**	**(0.38)**	**7.07**	**53%**	**100%**	-46%	-42%
	61%	3%	36%							
LDPE-coated Paperboard Cup									RPET SMX	
Cup	7.29	0.12	0.78	**8.18**	(0.18)	8.00	51%	95%	compared to Ppbd Cup	
Packaging	0.31	0.01	0.06	**0.39**	(0.01)	0.38	65%	4%	% Diff	% Diff
End of life	0.01	0.04	0.00	**0.05**		0.05	99%	1%	Total Energy	Net Energy
Total	7.61	0.17	0.84	**8.62**	**(0.19)**	**8.43**	**26%**	**100%**	-60%	-59%
	88%	2%	10%							
LDPE-coated Ppbd Cup									RPET SMX	
+ Corrugated Sleeve									compared to	
Cup + Sleeve	8.88	0.18	0.78	**9.84**	(0.22)	9.61	52%	95%	Ppbd Cup + Sleeve	
Packaging	0.38	0.01	0.06	**0.46**	(0.01)	0.45	63%	4%	% Diff	% Diff
End of life	0.01	0.04	0.00	**0.05**		0.05	99%	0%	Total Energy	Net Energy
Total	9.27	0.23	0.84	**10.34**	**(0.23)**	**10.11**	**25%**	**100%**	-76%	-75%
	88%	2%	10%							
OPEN-LOOP ALLOCATION										
RPET SMX										
Cup	4.66	0.19	1.16	**6.01**	(0.06)	5.96	91%	95%		
Packaging	0.26	0.01	0.01	**0.28**	(0.001)	0.28	68%	4%		
End of life	0.00	0.01	0.00	**0.02**		0.02	99%	0%		
Total	4.92	0.22	1.17	**6.31**	**(0.06)**	**6.25**	**90%**	**100%**		
	78%	3%	19%							
EPS									RPET SMX	
Cup	4.08	0.14	2.58	**6.80**	(0.37)	6.43	95%	92%	compared to EPS	
Packaging	0.39	0.02	0.12	**0.53**	(0.01)	0.51	78%	7%	% Diff	% Diff
End of life	0.01	0.04	0.00	**0.05**		0.05	99%	1%	Total Energy	Net Energy
Total	4.48	0.20	2.69	**7.38**	**(0.38)**	**6.99**	**53%**	**100%**	-16%	-11%
	61%	3%	37%							
LDPE-coated Paperboard Cup									RPET SMX	
Cup	7.29	0.12	0.78	**8.18**	(0.18)	8.00	51%	96%	compared to Ppbd Cup	
Packaging	0.26	0.01	0.06	**0.33**	(0.01)	0.32	76%	4%	% Diff	% Diff
End of life	0.01	0.04	0.00	**0.05**		0.05	99%	1%	Total Energy	Net Energy
Total	7.55	0.17	0.84	**8.56**	**(0.19)**	**8.38**	**27%**	**100%**	-30%	-29%
	88%	2%	10%							
LDPE-coated Ppbd Cup									RPET SMX	
+ Corrugated Sleeve									compared to	
Cup + Sleeve	8.57	0.17	0.78	**9.52**	(0.22)	9.30	54%	96%	Ppbd Cup + Sleeve	
Packaging	0.31	0.01	0.06	**0.39**	(0.01)	0.38	75%	4%	% Diff	% Diff
End of life	0.01	0.04	0.00	**0.05**		0.05	99%	1%	Total Energy	Net Energy
Total	8.89	0.23	0.84	**9.96**	**(0.23)**	**9.73**	**25%**	**100%**	-45%	-44%
	88%	2%	10%							

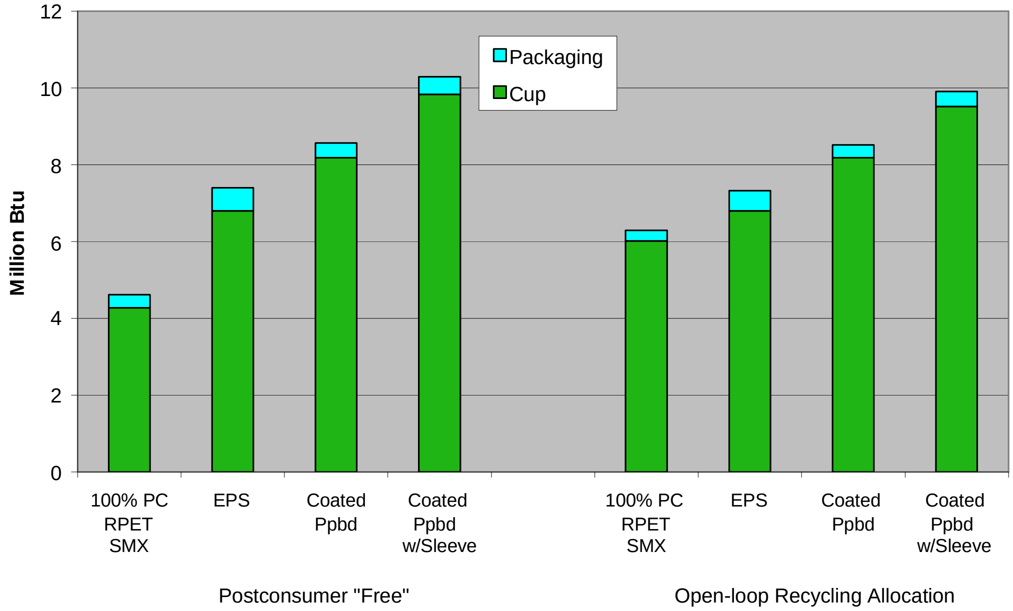
Source: Franklin Associates, A Division of ERG.

Figure 2-1. Total Energy by Category for 10,000 Cups and Packaging



For total energy, a percent difference of 10% or greater between 2 systems' results is considered significant.

Figure 2-2. Total Energy by Component for 10,000 Cups and Packaging



For total energy, a percent difference of 10% or greater between 2 systems' results is considered significant.

Energy Conclusions. The final column of Table 2-2 shows the percent difference in total energy requirements for the cup systems. Regardless of the recycling methodology used for the recycled content of the RPET SMX cup, the RPET SMX cup system has lower total energy requirements than the other cup systems.

Solid Waste

Solid waste results for each system are shown in Table 2-4 for solid waste by weight and Table 2-5 for solid waste by volume. Solid wastes are broadly categorized into process wastes, fuel-related wastes, and postconsumer wastes. **Process wastes** are the solid wastes generated by the various processes used to extract, transform, fabricate, or otherwise effect changes on materials and products throughout their life cycle. **Fuel-related wastes** are the wastes from the production and combustion of fuels used for process energy and transportation energy. **Postconsumer wastes** include postconsumer cups that are landfilled, as well as ash from municipal waste combustion of 20 percent of the postconsumer cups and packaging that are disposed.

Differences in solid waste results between systems are not considered meaningful unless the percent difference is greater than 25 percent for process and fuel-related wastes, or greater than 10 percent for postconsumer wastes. (Percent difference between systems is defined as the difference between solid waste totals divided by the average of the two system totals.) This minimum percent difference criterion was developed based on the experience and professional judgment of the analysts and supported by sample statistical calculations (see Appendix A).

Solid Waste by Weight. Table 2-3 and Figure 2-3 show solid waste by weight broken out into the categories of process waste, fuel-related waste, and postconsumer waste. Postconsumer cups and packaging account for the majority of the weight of solid waste for all systems. Fuel-related wastes are about twice as high as process wastes for most systems. For the RPET SMX cup, more than half of the fuel-related waste is associated with the electricity use for cup converting.

The EPS cup system has the lowest process wastes. For the RPET SMX system, there are no process wastes from cup converting operations, since all SMX foam scrap is recycled. Most of the process waste shown for the RPET SMX system is waste associated with postconsumer PET collection and reprocessing. For the paperboard cup system, the process wastes are mainly generated at paperboard mills. All paperboard cup converting scrap is sold for recycling.

The choice of recycling methodology has a large effect on the weight of postconsumer solid waste allocated to the RPET SMX cup system. In the "PC free" recycling methodology, all disposal burdens for the cup material are allocated to the cup system. In the open-loop allocation method, the disposal burdens for the cup material are divided between the two systems in which the PET is used (the virgin PET application and the RPET cup system), so that half of the postconsumer weight is assigned to each use. This difference can be seen by comparing the postconsumer segments for the RPET cups in Figure 2-3, which show approximately half as much postconsumer waste in the open-loop scenario.

Figure 2-4 shows solid waste by weight broken out by cups and packaging. Ninety percent or more of the total solid waste for each system is associated with the production and disposal of the cups (and cup sleeves). The contribution of packaging is greatest for the EPS cup system. The EPS cup walls are thicker and they have a larger rim compared to the other cups, giving them a greater stacking height; thus, 10,000 EPS cups take up more space and require larger size corrugated boxes for packaging compared to the other cups. For the paperboard cup with sleeve system, additional corrugated packaging is required for the sleeves; however, the added packaging per 10,000 cup sleeves is small, since the corrugated sleeves compact flat for shipping.

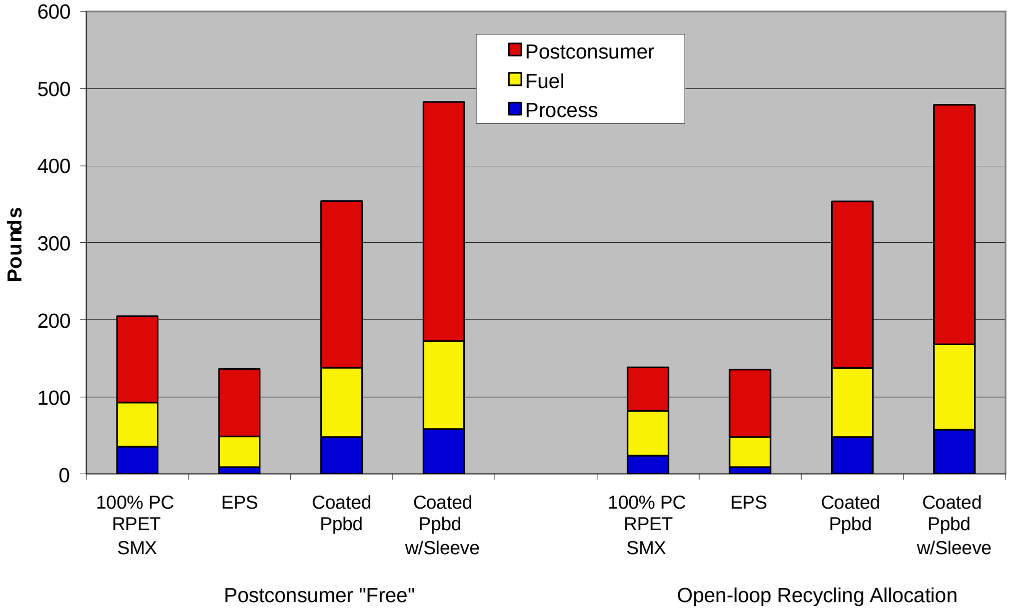
Conclusions for Weight of Solid Waste. The final column of Table 2-3 shows the percent differences in total solid waste for the cup systems. The conclusions regarding the foam cup systems differ depending on recycling methodology. For the PC free modeling, all the PC disposal burdens for the PET material are allocated to the cup system, so the RPET SMX solid waste is significantly higher than the EPS cup system solid waste. For the open-loop recycling modeling, the PET disposal burdens are allocated between the virgin PET application and the RPET cup system, and there is no significant difference between the RPET and EPS cup systems. For both recycling methodologies, the weight of solid waste for the RPET SMX cup system is significantly lower than the paperboard cup and the paperboard cup with sleeve.

TABLE 2-3. TOTAL WEIGHT OF SOLID WASTE FOR 10,000 CUPS AND PACKAGING
(Pounds)

	Process Wastes	Fuel-related Wastes	Postconsumer Wastes	**TOTAL WASTE**	**Component % of Total**	**% Difference in System Totals**
PC FREE						
RPET SMX						
Cup	33.8	52.3	111	**197**	96%	
Packaging	2.04	4.45	1.21	**7.70**	4%	
Total	**35.8**	**56.7**	**112**	**205**	**100%**	
	17%	28%	55%			
EPS						RPET SMX
Cup	6.18	33.6	82.8	**123**	90%	compared to
Packaging	2.85	6.08	4.96	**13.9**	10%	EPS
Total	**9.03**	**39.6**	**87.8**	**136**	**100%**	40%
	7%	29%	64%			
LDPE-coated Paperboard Cup						RPET SMX
Cup	45.9	86.0	214	**346**	98%	compared to
Packaging	1.92	4.11	2.81	**8.83**	2%	Ppbd
Total	**47.8**	**90.1**	**216**	**354**	**100%**	-54%
	13%	25%	61%			
LDPE-coated Ppbd Cup + Corrugated Sleeve						RPET SMX
Cup + Sleeve	56.2	108.6	307	**472**	98%	compared to
Packaging	2.35	5.07	3.00	**10.42**	2%	Ppbd + Sleeve
Total	**58.5**	**113.7**	**310**	**483**	**100%**	-81%
	12%	24%	64%			
OPEN-LOOP ALLOCATION						
RPET SMX						
Cup	21.9	54.0	56	**131**	95%	
Packaging	1.86	4.01	1.21	**7.08**	5%	
Total	**23.8**	**58.0**	**57**	**138**	**100%**	
	17%	42%	41%			
EPS						RPET SMX
Cup	6.18	33.6	82.8	**123**	90%	compared to
Packaging	2.63	5.51	4.96	**13.1**	10%	EPS
Total	**8.81**	**39.1**	**87.8**	**136**	**100%**	2%
	6%	29%	65%			
LDPE-coated Paperboard Cup						RPET SMX
Cup	45.9	86.0	214	**346**	98%	compared to
Packaging	1.76	3.72	2.81	**8.29**	2%	Ppbd
Total	**47.6**	**89.7**	**216**	**354**	**100%**	-87%
	13%	25%	61%			
LDPE-coated Ppbd Cup + Corrugated Sleeve						RPET SMX
Cup + Sleeve	55.3	106.3	307	**469**	98%	compared to
Packaging	2.16	4.58	3.00	**9.74**	2%	Ppbd + Sleeve
Total	**57.4**	**110.9**	**310**	**479**	**100%**	-110%
	12%	23%	65%			

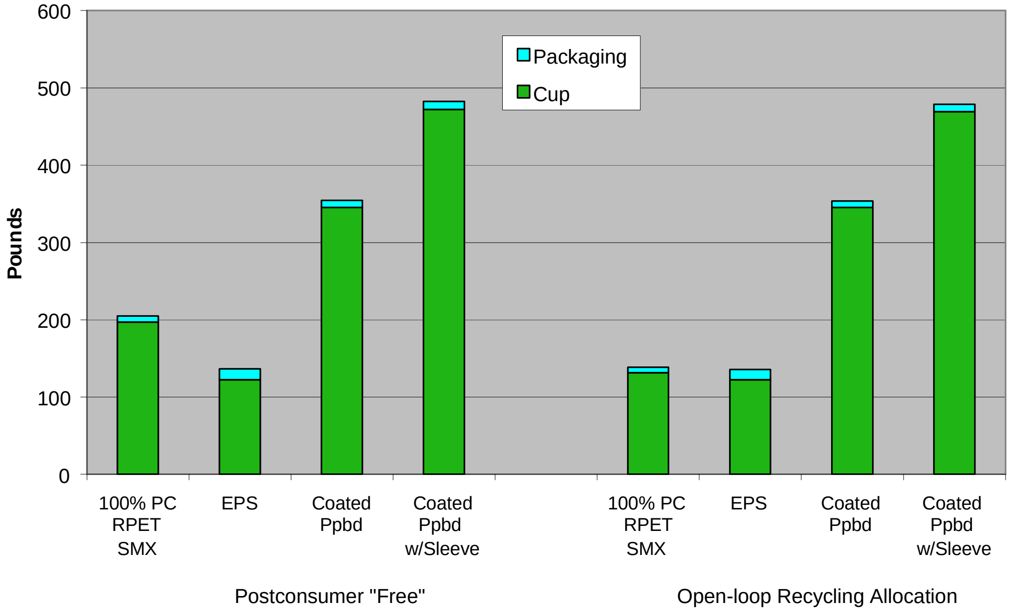
Source: Franklin Associates, A Division of ERG.

Figure 2-3. Total Weight of Solid Waste by Category for 10,000 Cups and Packaging



For solid waste, a percent difference of 25% or greater between 2 systems' overall results is considered significant.
For the weight of postconsumer solid waste only, a percent difference of 10% is considered significant.

Figure 2-4. Total Weight of Solid Waste by Component for 10,000 Cups and Packaging



For solid waste, a percent difference of 25% or greater between 2 systems' overall results is considered significant.
For the weight of postconsumer solid waste only, a percent difference of 10% is considered significant.

Solid Waste by Volume. While solid waste generation is commonly tracked in terms of weight, solid waste volume is the important issue in landfills. Weights of solid waste are converted to volume by dividing by their landfill density. An average density factor for industrial solid waste is used for process wastes, fuel-related wastes, and landfill ash. For RPET SMX cups, the density of the foamed material as produced (0.268 grams/cubic centimeter) is used as the landfill density. No projections are made on how the SMX cups might further compact in the landfill. The landfill densities of other landfilled cups and cup packaging materials are based on densities for similar types of packaging determined by landfill sampling studies.[33]

Table 2-4 and Figure 2-5 show the volume of solid waste by category, while Figure 2-6 shows the volume of solid waste by component. Although there are large differences in the weights of postconsumer cups of different types, when the weights are converted to volumes using the landfill densities of each cup material, the volumes of postconsumer cups show a narrower spread.

Conclusions for Volume of Solid Waste. The final column of Table 2-4 shows the percent differences in total solid waste for the cup systems. For the “PC free” scenario, there is no significant difference in the total solid waste volume for the three cup systems, although results for the paperboard cup system are significantly higher when a corrugated cup sleeve is used. For the open-loop recycling scenario, total solid waste volume for the RPET SMX cup is significantly lower than all other systems.

Environmental Emissions

In this LCI, the evaluation of emissions is limited to greenhouse gas emissions. These include emissions released directly from processes (e.g., fugitive methane emissions from natural gas extraction and processing, emissions from chemical reactions, releases of carbon dioxide used in the SMX expansion process) and those associated with the combustion of fuels used for process and transportation energy. As described in the **End-of-Life Management** section in Chapter 1, this analysis also includes estimates of the greenhouse gas emissions resulting from end-of-life management of packaging system components, including those from WTE combustion of packaging materials, methane emissions from decomposition of landfilled paperboard, and credits for grid electricity emissions that are displaced by energy recovered from WTE combustion of materials and captured landfill gas, and carbon sequestration in landfilled biomass-derived materials that do not decompose.

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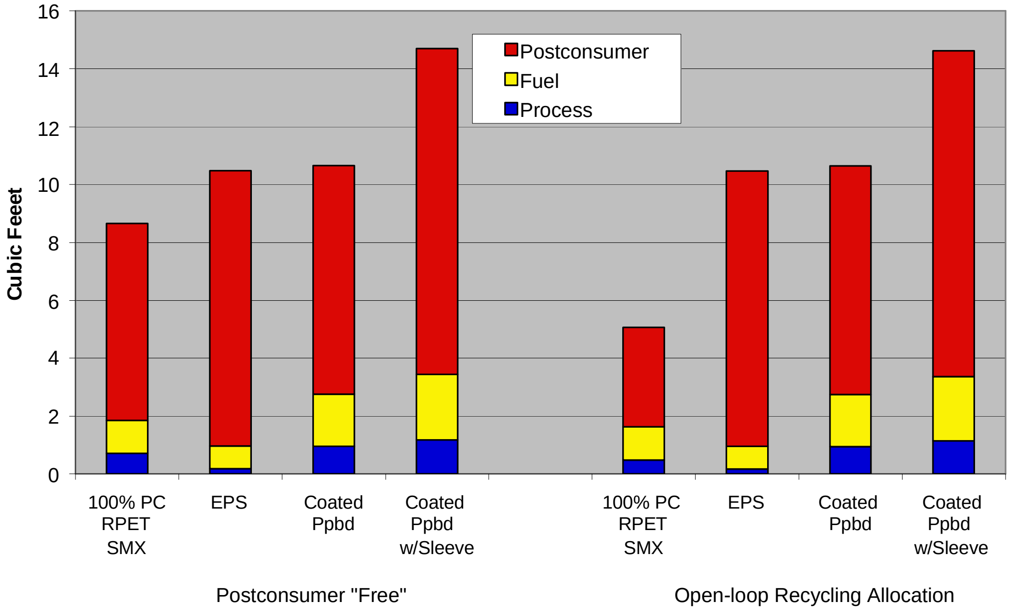
[33] **Estimates of the Volume of MSW and Selected Components in Trash Cans and Landfills.** Prepared for The Council for Solid Waste Solutions by Franklin Associates, Ltd. and The Garbage Project. February 1990.

TABLE 2-4. TOTAL VOLUME OF SOLID WASTE FOR 10,000 CUPS AND PACKAGING
(Cubic Feet)

	Process Wastes	Fuel-related Wastes	Postconsumer Wastes	**TOTAL WASTE**	**Component % of Total**	**% Difference in System Totals**
PC FREE						
RPET SMX						
Cup	0.68	1.05	6.76	**8.48**	98%	
Packaging	0.04	0.09	0.04	**0.17**	2%	
Total	**0.72**	**1.13**	**6.81**	**8.66**	**100%**	
	8%	13%	79%			
EPS						RPET SMX
Cup	0.12	0.67	9.32	**10.11**	96%	compared to
Packaging	0.06	0.12	0.20	**0.37**	4%	EPS
Total	**0.18**	**0.79**	**9.51**	**10.49**	**100%**	-19%
	2%	8%	91%			
LDPE-coated Paperboard Cup						RPET SMX
Cup	0.92	1.72	7.79	**10.42**	98%	compared to
Packaging	0.04	0.08	0.11	**0.23**	2%	Ppbd
Total	**0.96**	**1.80**	**7.90**	**10.65**	**100%**	-21%
	9%	17%	74%			
LDPE-coated Ppbd Cup + Corrugated Sleeve						RPET SMX
Cup + Sleeve	1.12	2.17	11.14	**14.44**	98%	compared to
Packaging	0.05	0.10	0.12	**0.27**	2%	Ppbd + Sleeve
Total	**1.17**	**2.27**	**11.26**	**14.70**	**100%**	-52%
	8%	15%	77%			
OPEN-LOOP ALLOCATION						
RPET SMX						
Cup	0.44	1.08	3.38	**4.90**	97%	
Packaging	0.04	0.08	0.04	**0.16**	3%	
Total	**0.48**	**1.16**	**3.43**	**5.06**	**100%**	
	9%	23%	68%			
EPS						RPET SMX
Cup	0.12	0.67	9.32	**10.11**	97%	compared to
Packaging	0.05	0.11	0.20	**0.36**	3%	EPS
Total	**0.18**	**0.78**	**9.51**	**10.47**	**100%**	-70%
	2%	7%	91%			
LDPE-coated Paperboard Cup						RPET SMX
Cup	0.92	1.72	7.79	**10.42**	98%	compared to
Packaging	0.04	0.07	0.11	**0.22**	2%	Ppbd
Total	**0.95**	**1.79**	**7.90**	**10.64**	**100%**	-71%
	9%	17%	74%			
LDPE-coated Ppbd Cup + Corrugated Sleeve						RPET SMX
Cup + Sleeve	1.11	2.13	11.14	**14.37**	98%	compared to
Packaging	0.04	0.09	0.12	**0.25**	2%	Ppbd + Sleeve
Total	**1.15**	**2.22**	**11.26**	**14.62**	**100%**	-97%
	8%	15%	77%			

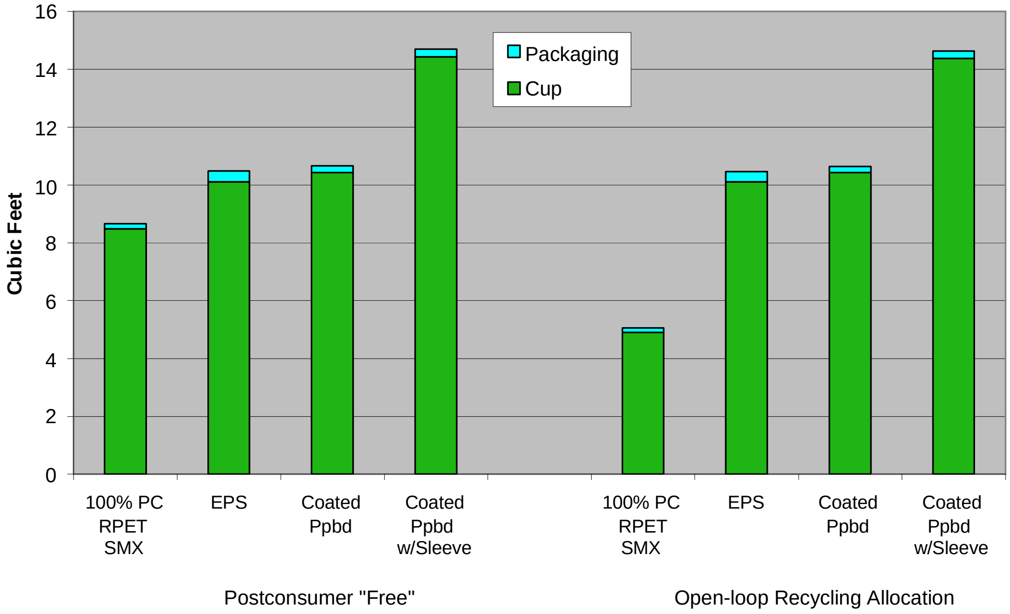
Source: Franklin Associates, A Division of ERG.

Figure 2-5. Total Solid Waste Volume by Category for 10,000 Cups and Packaging



For volume of solid waste, a percent difference of 25% or greater between 2 systems' overall results is considered significant.

Figure 2-6. Total Solid Waste Volume by Component for 10,000 Cups and Packaging



For volume of solid waste, a percent difference of 25% or greater between 2 systems' overall results is considered significant.

The emissions results in this section are based upon the best data available. Some emissions data are reported from industrial sources, and others are based on engineering estimates or published emission factors. Because of these uncertainties, the difference in two systems' emissions of a given substance are not considered meaningful unless the percent difference exceeds 25 percent. (Percent difference is defined as the difference between two system totals divided by their average.) This minimum percent difference criterion was developed based on the experience and professional judgment of the analysts and supported by sample statistical calculations (see Appendix A). If the percent difference between two systems' results is less than 25 percent, the comparison is considered inconclusive.

The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. Because different greenhouse gases have different global warming "potencies", global warming potential (GWP) factors are used to normalize emissions of different substances to a common basis of carbon dioxide equivalents. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide, which is assigned a GWP of 1.

The GWP factors that are most widely used are those from the International Panel on Climate Change (IPCC) Second Assessment Report (SAR), published in 1996. Although two subsequent updates of the IPCC report with slightly different GWPs have been published since the SAR, the GWPs from the SAR are used for consistency with international reporting standards.[34] The IPCC SAR 100-year global warming potentials (GWP) are 21 for methane and 310 for nitrous oxide. The weight of each GHG emission is multiplied by its GWP, then the carbon dioxide equivalents are summed to arrive at the totals shown in Table 2-5.

Greenhouse gas emissions generally track closely with fossil fuel energy requirements, since the majority of GHG emissions are carbon dioxide from the combustion of fossil fuels used for process and transportation energy over the life cycle of the cup systems. For the energy category of Energy of Material Resource, which tracks the energy content of oil and natural gas used as material inputs for plastics, GHG emissions are released only for the portion of the plastic materials that is burned at end of life.

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[34] The United Nations Framework Convention on Climate Change reporting guidelines for national inventories continue to use GWPs from the IPPC Second Assessment Report (SAR). For this reason, the U.S. EPA also uses GWPs from the IPCC SAR, as described on page ES-1 of EPA 430-R-08-005 **Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006** (April 15, 2008).

TABLE 2-5. TOTAL GLOBAL WARMING POTENTIAL FOR 10,000 CUPS AND PACKAGING
(Pounds of CO2 Equivalents)

	Process GWP	Fuel-related GWP	End of Life Net GWP	**TOTAL GWP**	**Component % of Total**	**% Difference in System Totals**
PC FREE						
RPET SMX						
Cup	32.8	654	44.7	**731**	95%	
Packaging	0.16	37.2	-0.71	**36.6**	5%	
Total	**33.0**	**691**	**44.0**	**768**	**100%**	
	4%	90%	6%			
EPS						RPET SMX
Cup	51.6	625	46.3	**722**	93%	compared to
Packaging	0.68	57.1	0.24	**58.1**	7%	EPS
Total	**52.3**	**682**	**46.5**	**780**	**100%**	-2%
	7%	87%	6%			
LDPE-coated Paperboard Cup						RPET SMX
Cup	6.62	638	115	**759**	95%	compared to
Packaging	0.38	37.6	1.05	**39.0**	5%	Ppbd
Total	**7.00**	**676**	**116**	**798**	**100%**	-4%
	1%	85%	14%			
LDPE-coated Ppbd Cup + Corrugated Sleeve						RPET SMX
Cup + Sleeve	7.25	824	337	**1,168**	96%	compared to
Packaging	0.41	45.4	1.14	**47.0**	4%	Ppbd + Sleeve
Total	**7.66**	**869**	**338**	**1,215**	**100%**	-45%
	1%	72%	28%			
OPEN-LOOP ALLOCATION						
RPET SMX						
Cup	59.1	741	22.4	**823**	96%	
Packaging	0.06	37.6	-0.71	**36.9**	4%	
Total	**59.2**	**779**	**21.6**	**859**	**100%**	
	7%	91%	3%			
EPS						RPET SMX
Cup	51.6	625	46.3	**722**	93%	compared to
Packaging	0.55	57.6	0.24	**58.4**	7%	EPS
Total	**52.1**	**682**	**46.5**	**781**	**100%**	10%
	7%	87%	6%			
LDPE-coated Paperboard Cup						RPET SMX
Cup	6.62	638	115	**759**	95%	compared to
Packaging	0.29	37.9	1.05	**39.3**	5%	Ppbd
Total	**6.91**	**676**	**116**	**798**	**100%**	7%
	1%	85%	14%			
LDPE-coated Ppbd Cup + Corrugated Sleeve						RPET SMX
Cup + Sleeve	6.72	826	340	**1,172**	96%	compared to
Packaging	0.30	45.9	1.14	**47.3**	4%	Ppbd + Sleeve
Total	**7.02**	**872**	**341**	**1,220**	**100%**	-35%
	1%	71%	28%			

Source: Franklin Associates, A Division of ERG.

For paperboard cups and corrugated packaging, carbon dioxide emissions from the use of wood-derived energy in paperboard mills are considered part of the natural carbon cycle and are not included in the GHG totals as a net contribution to atmospheric carbon dioxide. Similarly, carbon dioxide emissions from WTE combustion of paper products are also considered carbon neutral, since they return the carbon content of the material to the atmosphere in the same form in which it was taken up during the tree's growth cycle.

Greenhouse gas results for the cup systems are shown by category in Figure 2-7 and by component in Figure 2-8. For the RPET SMX and EPS cup systems, greenhouse gas emissions from combustion of process and transportation fuels are the dominant contributor to total GWP. Although the carbon dioxide used in the SMX saturation/expansion process is currently released without recovery or recycling, the total process emissions for the RPET SMX cup, including these carbon dioxide emissions, account for only about 5 percent of the total process and fuel-related GWP for the RPET SMX cup system. The largest share of fuel-related GWP for the SMX cup system is associated with the electricity used for cup converting.

Because the RPET and EPS cups do not decompose in landfills, end-of-life disposal of cups does not make a very large contribution to the total GWP for these systems. The end-of-life GWP shown for the plastic foam cups is the carbon dioxide released from WTE combustion of 20 percent of disposed cups minus a credit for grid electricity GWP displaced by the recovered energy.

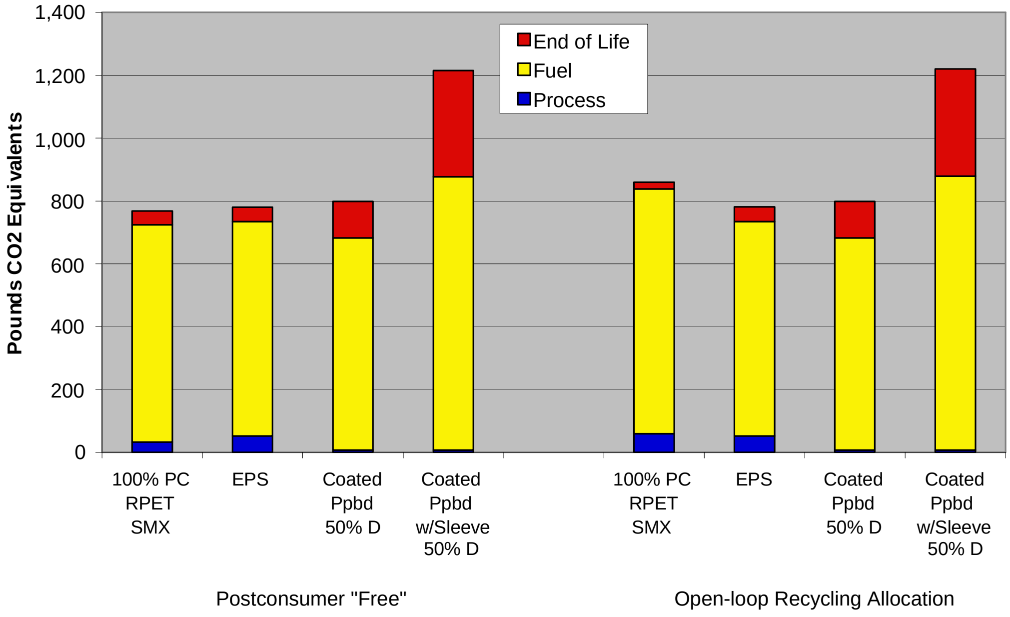
For the paperboard cup system, corrugated sleeve, and corrugated packaging, the end-of-life GWP includes credits for WTE combustion, but impacts are also modeled based on some decomposition of paperboard components in the landfill. The results shown are based on 50 percent of the maximum decomposition observed in landfill simulation experiments by Barlaz, as described in the **End of Life Management** section of Chapter 1. Results for additional decomposition scenarios are shown in the **Sensitivity Analysis** section of this chapter.

Sensitivity to GWP Factors. As noted previously, this analysis uses GWP factors from the IPCC 1996 Second Assessment Report (methane = 21, nitrous oxide = 310) for consistency with international reporting standards. More recent IPCC reports use slightly different GWP factors. The majority of the GWP for each system is from carbon dioxide, which is assigned a reference GWP of 1 in all IPCC reports. A sensitivity analysis was conducted to determine the effect on GWP results of using GWP factors for methane and nitrous oxide from the IPCC 2007 report (methane = 25, nitrous oxide = 298).

The effect on total system GWP for use of 2007 GWP factors compared to 1996 factors was small for the plastic cup systems, ranging from a 1 percent increase for the RPET SMX system to a 1.6 percent increase for the EPS system. The percent increase for the paperboard cup and the paperboard cup with sleeve was larger, about 4 percent. Methane from landfill decomposition of paperboard makes a large contribution to the end-of-life GWP for the paperboard cup systems, so changing the methane GWP from 21 to 25 has a larger effect on the paperboard systems than the plastic systems.

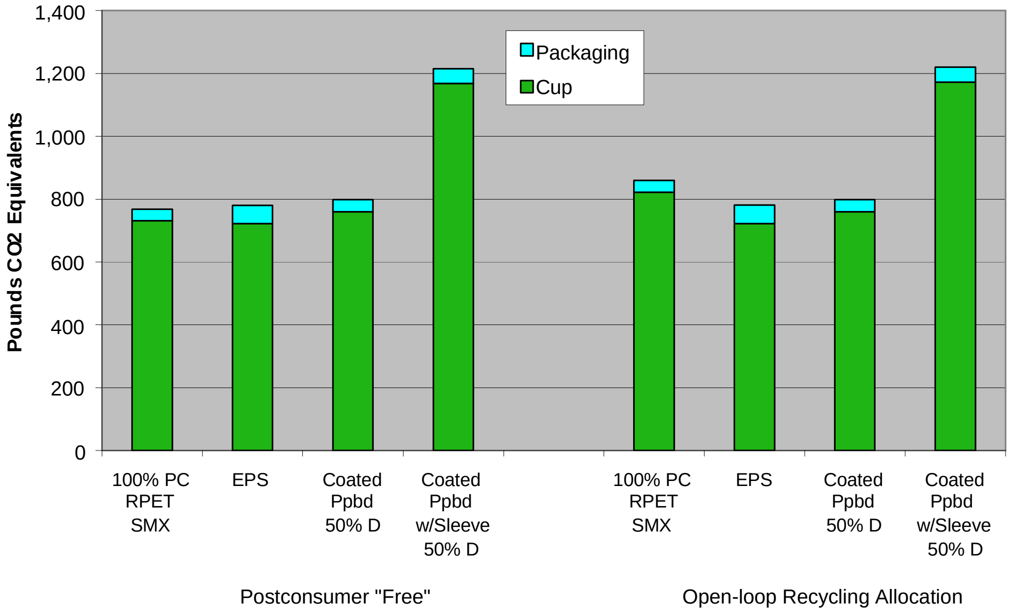
Global Warming Potential Conclusions. There is not a significant difference in total GWP among the three baseline cup systems when end-of-life impacts are included, except, however, that the paperboard cup with sleeve system has significantly higher results than the cup systems without sleeves, due to the additional contribution to GHG from decomposition of those sleeves. The end-of-life GWP estimates are more uncertain than process and fuel-related GWP calculations because the end-of-life GWP estimates include some projections about the decomposition of paperboard in landfills, which can vary greatly depending on conditions at individual landfills. The end-of-life GWP estimates are also based on the composite national average for capture and management of landfill gas, which varies from landfill to landfill. Also, the decomposition emissions occur over a very long period of time compared to the process and fuel-related emissions.

Figure 2-7. Total Global Warming Potential by Category for 10,000 Cups and Packaging



For GWP, a percent difference of 25% or greater between 2 systems' overall results is considered significant.

Figure 2-8. Total Global Warming Potential by Component for 10,000 Cups and Packaging



For GWP, a percent difference of 25% or greater between 2 systems' overall results is considered significant.

SENSITIVITY ANALYSIS

The figures in this section present energy and greenhouse gas results for different scenarios for paperboard cups based on variations in the fuel mix for bleached paperboard production and assumptions about decomposition of landfilled paperboard.

The results tables and figures shown in other sections of this chapter include results for both cups and cup packaging. The results in the sensitivity section are for cups only (and the corrugated sleeve option with the paperboard cup); packaging is not included.

Energy Results

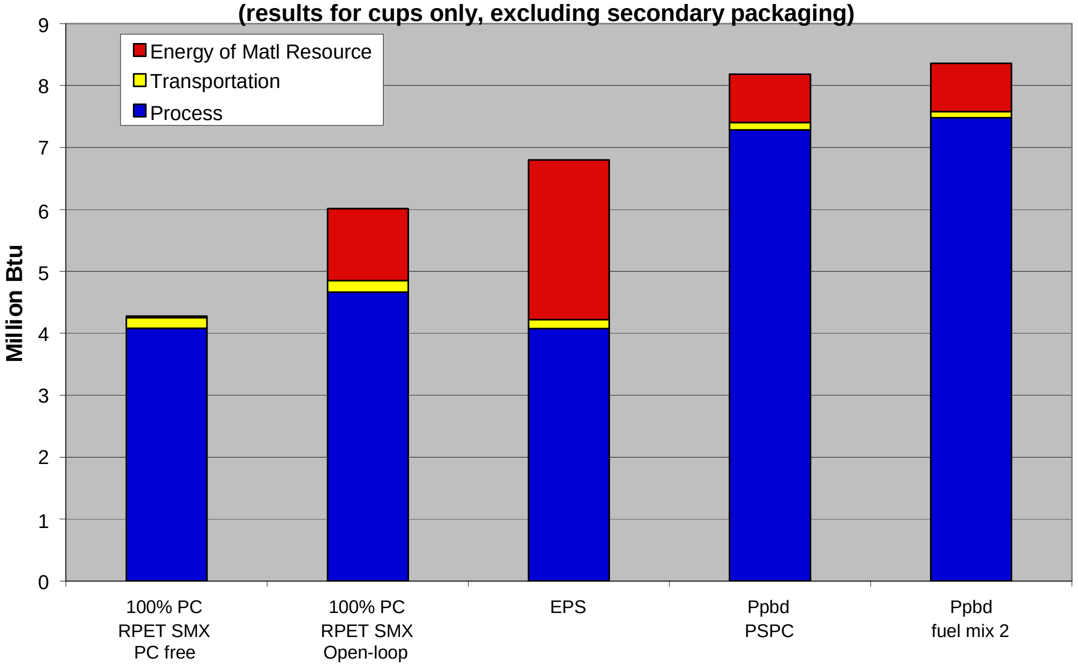
Figure 2-9 shows the variations in total energy requirements for paperboard cups for different paperboard mill fuel mixes. The figure shows that the total energy requirements are quite similar for the two averages, despite the variations in the types and quantities of fuels used at the different mills.

Greenhouse Gas Results

Although the different fuel mixes evaluated for paperboard production had a small effect on total energy results, Figure 2-10 shows that there is a very large effect on greenhouse gas results depending on the mix of wood-derived energy and fossil-derived energy used at individual paperboard mills. Fuel mix 2 is based on an average fuel mix including a paperboard mill that used less wood-derived energy and significantly more coal than the other mills. This has a large effect on GWP, since carbon dioxide emissions from combustion of wood wastes are considered carbon neutral, but carbon dioxide from combustion of fossil fuels adds to the net GWP. As shown in Figure 2-10, when the fuel mix variations are combined with variations in end-of-life decomposition modeling, the total life cycle GWP results for paperboard cups can vary by nearly a factor of two.

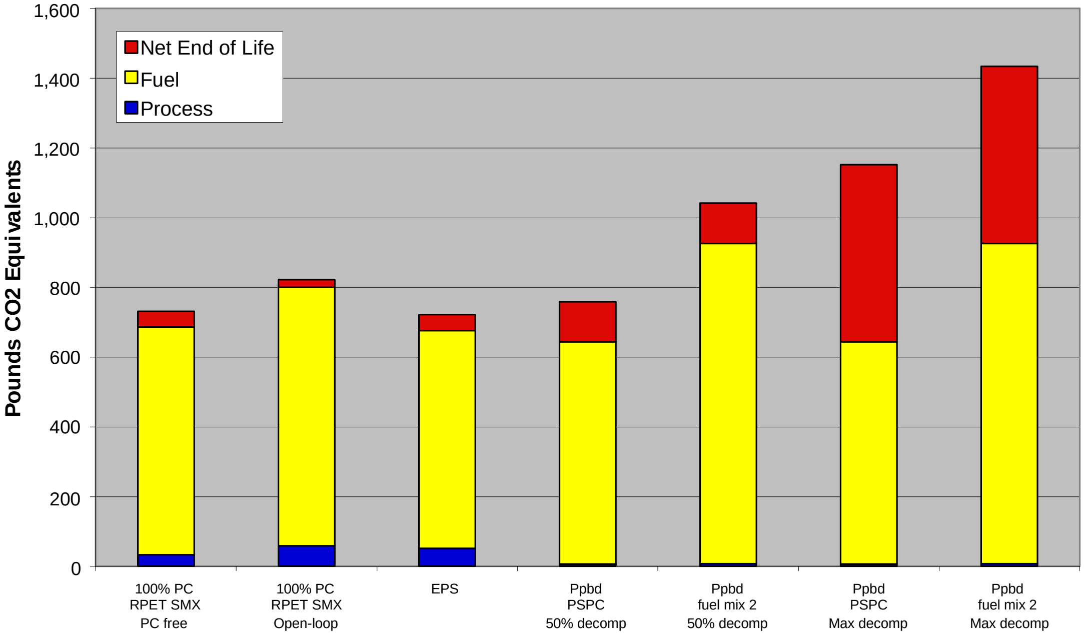
The sensitivity analysis shows that the fuel-related GWP results for a paperboard product can be greatly affected by the fuel mix at the mill where the paperboard is produced. In addition, the net end-of-life GWP for paperboard products varies widely depending on the degree of decomposition that occurs in the landfill. Decomposition occurs over a much longer period of time compared to releases of process and fuel-related emissions, and the degree of decomposition will vary depending on conditions such as moisture, temperature, pH, etc. at individual landfills, as well as how landfill gas emissions are managed at that site. Coatings are also expected to inhibit decomposition. The dependency of results on paperboard mill fuel mix, conditions at the landfill site where products are disposed, and management of landfill gas at that location make it difficult to draw broadly applicable conclusions about the total life cycle GWP for paperboard products.

Figure 2-9. Total Energy for 10,000 Cups:
Sensitivity to Paperboard Production Fuel Mix
(results for cups only, excluding secondary packaging)



For total energy, a percent difference of 10% or greater between 2 systems' results is considered significant.

Figure 2-10. Total Global Warming Potential for 10,000 Cups: Sensitivity to Paperboard Production Fuel Mix and Paperboard Decomposition (results for cups only, excluding secondary packaging)



For GWP, a percent difference of 25% or greater between 2 systems' results is considered significant.

RPET SMX CUP RECYCLING SCENARIO

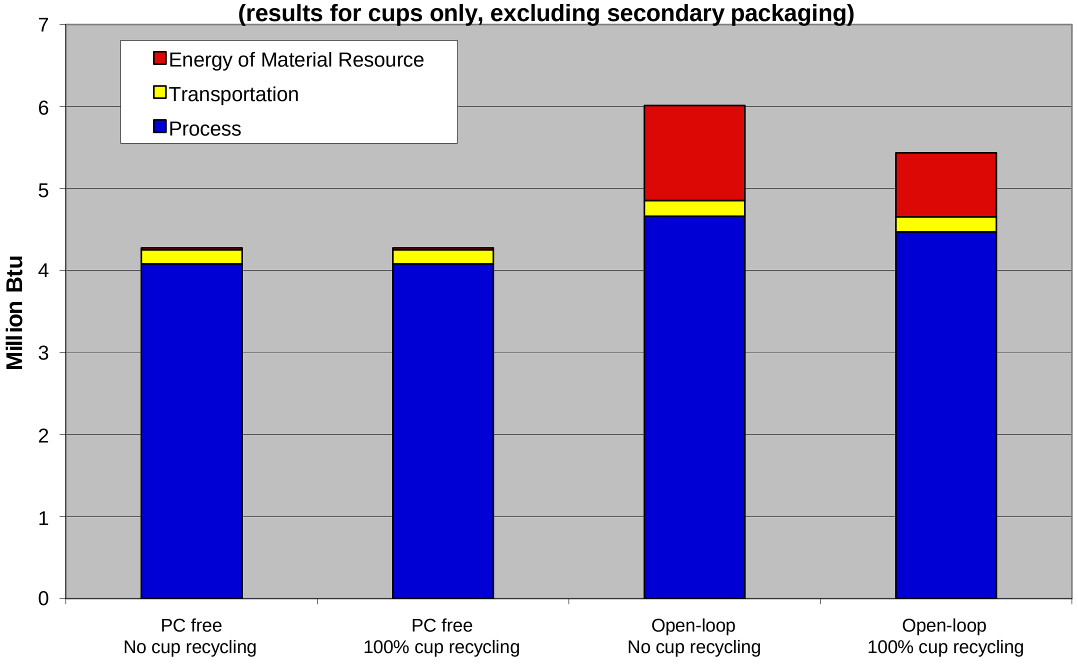
The cups in this analysis are disposable cups, intended for a single use. There is currently very little postconsumer recycling of disposable foodservice items due to a number of factors, including problems associated with food residues and the fact that foodservice products are often disposed in a mixed-material stream (e.g., together with napkins, plastic utensils, aluminum cans, PET bottles, etc.), necessitating sorting and separation. Even if foodservice products were sorted by material, there is not a widespread infrastructure for recycling of some foodservice product materials such as EPS and coated paperboard. For EPS cups, the low density of the material presents additional difficulties in cost-effectively transporting collected material to a reprocessing location. For coated paperboard cups, the coating must be separated from the fiber before the paperboard can be recycled. While there have been some pilot programs for recycling foodservice items, these have tended to be linked to cafeteria operations generating large volumes of specific types of postconsumer material (i.e., so that material sorting and transportation requirements are minimized).

The RPET SMX cup has some advantages for potential recycling compared to the EPS and coated paperboard cups. The SMX cup is thinner and more flexible than EPS, so the SMX cups will compact more efficiently for transportation. The SMX cup has no coatings or additives that would complicate recycling processes, and it is made from PET, a material for which there is an established recycling infrastructure.

There are still challenges to be overcome, however. Recyclers are accustomed to seeing PET in the form of clear bottles. RPET SMX cups look like paperboard, and recycling personnel seeing these cups in a mixed waste stream would almost certainly identify them as paperboard and remove them from the PET recycling stream. Thus, the cups would need to be marked in some way so that they could readily be identified as PET, and recycling personnel would need to be trained to identify them. However, this problem could be minimized if a coffee shop, cafeteria, or other venue were to use *only* RPET SMX cups, so that recovered cups could be delivered to a recycler without requiring additional sorting.

Figures 2-11 and 2-12 show the effect that recycling of RPET SMX cups would have on the cups' energy and solid waste results. In Figure 2-11, there is very little change in energy for SMX cup recycling when the "PC free" scenario is used. Since this method already models the recycled content as free of virgin burdens, the small reduction is due to avoiding energy use for disposal of the cups. For the open-loop recycling modeling, the cup production energy is reduced by cup recycling. Instead of two useful lives (virgin use, RPET SMX cup use), the material production burdens are now divided over three useful lives (virgin use, RPET SMX cup use, subsequent use).

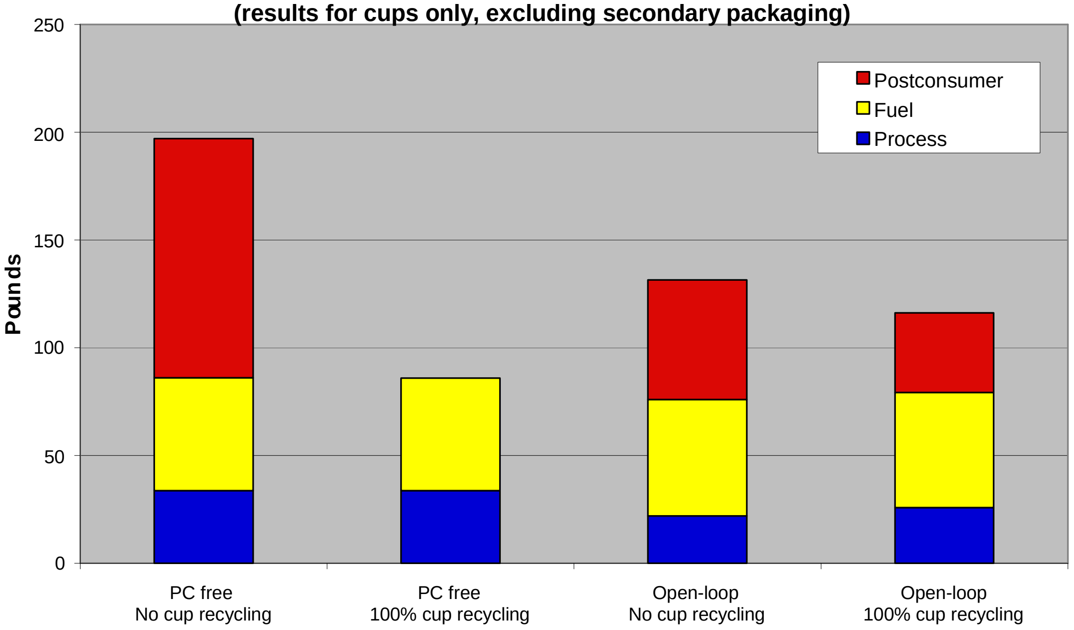
Figure 2-11. Total Energy for 10,000 Cups:
Sensitivity to SMX Cup Recycling
(results for cups only, excluding secondary packaging)



For total energy, a percent difference of 10% or greater between 2 systems' results is considered significant.

For solid waste, in the "PC free" scenario, recycling of the cups has a very large effect on the solid waste. In this methodology, the solid waste burdens go with the material into its next useful life, so there are no postconsumer solid waste burdens for cups that are recycled. Postconsumer disposal burdens are also reduced for the open-loop recycling scenario, but to a lesser extent; the disposal burdens are divided over three useful lives instead of two.

Figure 2-12. Total Weight of Solid Waste for 10,000 Cups: Sensitivity to SMX Cup Recycling (results for cups only, excluding secondary packaging)



For solid waste, a percent difference of 25% or greater between 2 systems' overall results is considered significant.
For the weight of postconsumer solid waste only, a percent difference of 10% is considered significant.

SUMMARY OF OBSERVATIONS AND CONCLUSIONS

In the following summary, the minimum percent difference between two systems' results for the difference to be considered significant is 10% for energy results and weight of postconsumer solid waste, and 25% for weight of process and fuel-related solid wastes, volume of solid waste, and GWP.

- **Recycled Content.** An important differentiating factor between the RPET SMX cup and the EPS and paperboard cups is the use of postconsumer resin in the SMX cup. The other cups are produced from virgin materials. Results in Chapter 2 represent RPET with 100% postconsumer content. It is more typical for RPET film in the current market to contain some mix of postconsumer and postindustrial recycled content. Results for cups made from RPET with 50% postconsumer content and 50% postindustrial content are presented in Appendix B. The results for 100% postconsumer

RPET should be considered as the most favorable scenario for RPET SMX cups.

- **Recycling Methodology.** Different methods can be used for allocating virgin material burdens among product systems that produce and use recycled material. Two approaches were used in this analysis. Conclusions about the relative environmental profiles for RPET SMX cups and other types of cups depend in some cases upon the methodology used to assign burdens to the postconsumer resin used in the RPET SMX cup.
- **Energy.** The light weight of the RPET SMX cup and its use of 100% postconsumer recycled resin both help reduce the energy requirements for the SMX cup. Regardless of the recycling methodology used to allocate burdens for the recycled content, the RPET SMX cup system has lower total energy requirements than the other cup systems.
- **Weight of Solid Waste.** For the PC free modeling, all the PC disposal burdens for the PET are allocated to the cup system, so the RPET SMX solid waste is significantly higher than the EPS cup system solid waste. For the open-loop recycling modeling, the PET disposal burdens are allocated between the virgin PET application and the RPET cup system, and there is no significant difference between the RPET and EPS cup systems. For both recycling methodologies, the weight of solid waste for the RPET SMX cup system is significantly lower than the paperboard cup and the paperboard cup with sleeve.
- **Volume of Solid Waste.** For the “PC free” scenario, there is no significant difference in the total solid waste volume for the three cup systems, although results for the paperboard cup system are significantly higher when a corrugated cup sleeve is used. For the open-loop recycling scenario, total solid waste volume for the RPET SMX cup system is significantly lower than all other systems.
- **Global Warming Potential for Cup Production.** There is not a significant difference in process and fuel-related GWP for the three cup systems when the paperboard cup is modeled using the same mix of paperboard mill fuels used in the PSPC study. Sensitivity analysis shows that the fuel-related emissions for the paperboard cup are strongly affected by the mix of wood-derived and fossil fuels used for process energy at the paperboard mill. Depending on the fuels used at a specific paperboard mill, the paperboard cup could have higher or lower GWP compared to the plastic foam cups.
- **End-of-Life Global Warming Potential**. The end-of-life GWP estimates are more uncertain than process and fuel-related GWP calculations because the end-of-life GWP estimates include projections and assumptions about the decomposition of paperboard in landfills and the management of landfill gas, which can vary greatly depending on conditions at individual landfills. End-of-life GWP for paperboard items were modeled for a scenario in which the degree of decomposition was 50 percent of the maximum degree of decomposition in landfill simulation experiments and landfill gas management was based on the national

average composite. For this scenario, there was no significant difference in total life cycle GWP for the three cup systems; however, with the addition of decomposition emissions for cups and sleeves, the GWP for the paperboard cup with sleeve had significantly higher results than the cup systems without sleeves.

- **RPET SMX Cup Recycling.** RPET SMX cups have characteristics that make them a good potential candidate for postconsumer recycling. Postconsumer recycling of SMX cups would further reduce their environmental profile compared to the environmental profile for cups that are disposed after use. The reduction is most significant for the solid waste results, particularly when the PC free methodology is used.
- **RPET SMX Improvement Opportunities.** In the sequence of processes used to convert RPET film to SMX cups, the cup converting process uses the most energy and has the highest greenhouse gas emissions (associated with the electricity used). The next most energy-intensive process is the saturation process. The direct process emissions of carbon dioxide released from the saturation and desaturation processes are small in comparison to fuel-related greenhouse gas emissions. Because process scrap is recycled, there is very little solid waste from the SMX cup process steps other than fuel-related waste. The greatest amount of process solid waste from the SMX system is associated with collection and reprocessing of postconsumer PET used in the RPET film, which was modeled based on single-stream curbside collection of recyclables.

APPENDIX A

CONSIDERATIONS FOR INTERPRETATION OF DATA AND RESULTS

INTRODUCTION

An important issue with LCI results is whether two numbers are really different from one another. For example, if one product has a total system requirement of 100 energy units, is it really different from another product system that requires 110 energy units? If the error or variability in the data is sufficiently large, it cannot be concluded that the two numbers are actually different.

STATISTICAL CONSIDERATIONS

A statistical analysis that yields clear numerical answers would be ideal, but unfortunately LCI data are not amenable to this. The data are not (1) random samples from (2) large populations that result in (3) "normal curve" distributions. LCI data meet none of these requirements for statistical analysis. LCI data for a given sub-process (such as potato production, roundwood harvesting, or caustic soda manufacture, for example) are generally selected to be representative of a process or industry, and are typically calculated as an average of two to five data points. In statistical terminology, these are not random samples, but "judgment samples," selected so as to reduce the possible errors incurred by limited sampling or limited population sizes. Formal statistics cannot be applied to judgment samples; however, a hypothetical data framework can be constructed to help assess in a general sense the reliability of LCI results.

The first step in this assessment is reporting standard deviation values from LCI data, calculated by:

$$\mathrm{s} = \sqrt{\frac{\sum (x_1 - x_{mean})^2}{n-1}},$$

where x_i is a measured value in the data set and x_{mean} is the average of n values. An analysis of sub-process data from Franklin Associates, Ltd. files shows that, for a typical sub-process with two to five different companies supplying information, the standard deviation of the sample is about 30 percent of the sample average.

In a typical LCI study, the total energy of a product system consists of the sum of many sub-processes. For the moment, consider an example of adding only two numbers. If both numbers are independent of each other and are an average of measurements which have a sample standard deviation, s, of 30, the standard deviation of the sum is obtained by adding the variances of each term to form the sum of the variances, then taking the square root. Variances are calculated by squaring the standard deviation, s^2, so the sum of the variances is $30^2 + 30^2 = 900 + 900 = 1800$. The new standard deviation of the sum is the square root of the sum of the variances, or $\sqrt{1800} = 42.4$. In this example, suppose both average values are 100, with a sum of 200. If reported as a percent of the sum, the new standard deviation is 42.4/200 = 21.3% of the sum. Another way of obtaining this value is to use the formula $s_{\%} = \frac{s/x_{mean}}{\sqrt{n}}$, where the term $s_{\%}$ is defined as the standard deviation of n data points, expressed as a % of the average, where each entry has approximately the same standard deviation, s. For the example, then, $s_{\%} = \frac{30\%}{\sqrt{2}} = 21.3\%$.

Going back to a hypothetical LCI example, consider a common product system consisting of a sum of approximately 40 subsystems. First, a special hypothetical case is examined where *all of the values are approximately the same size, and all have a standard deviation of 30%.* The standard deviation in the result is $s_{\%} = \frac{30\%}{\sqrt{40}} = 4.7\%$. The act of summing reduces the standard deviation of the result with respect to the standard deviation of each entry because of the assumption that errors are randomly distributed, and by combining values there is some cancellation of total error because some data values in each component system are higher than the true values and some are lower.

The point of this analysis, however, is to compare two results, e.g., the energy totals for two different product systems, and decide if the difference between them is significant or not. To test a hypothetical data set it will be assumed that two product systems consist of a sum of 40 values, and that the standard deviation, $s_{\%}$, is 4.7% for each product system.

If there is statistical knowledge of the sample only, and not of the populations from which they were drawn, "t" statistics can be used to find if the two product totals are different or not. The expression selected is:
$\mu 1 - \mu 2 = x1 - x2 +/- t_{.025} s' \sqrt{\frac{1}{n1} + \frac{1}{n2}}$, where $\mu 1 - \mu 2$. is the difference in population means, x_1-x_2 is the difference in sample means, and s' is a pooled standard deviation of the two samples. For the hypothetical case, where it is assumed that the standard deviation of the two samples is the same, the pooled value is simply replaced with the standard deviation of the samples.

The goal is to find an expression that compares our sample means to "true," or population, means. A new quantity is defined:
$\Delta = (\mu 1 - \mu 2) - (x1 - x2)$, and the sample sizes are assumed to be the same (i.e., n_1=n_2). The result is $\Delta = t_{.025} s' \sqrt{\frac{2}{n}}$, where Δ is the minimum difference corresponding to a 95%

confidence level, s' is the standard deviation of the sum of n values, and $t_{.025}$ is a t statistic for 95% confidence levels. The values for t are a function of n and are found in tables. This expression can be converted to percent notation by dividing both sides by the average of the sample means, which results in $\Delta\% = t_{.025} s'\% \sqrt{\frac{2}{n}}$, where $\Delta\%$ is now the percent difference corresponding to a 95% confidence level, and s'% is the standard deviation expressed as a percent of the average of the sample means. This formula can be simplified for the example calculation by remembering that $s'\% = \frac{s\%}{\sqrt{n}}$, where s% is the standard deviation of each energy entry for a product system. Now the equation becomes $\Delta\% = t_{.025} s\% \frac{\sqrt{2}}{n}$. For the example, t = 2.0, s = 30%, and n = 40, so that $\Delta\%$ = 2.1%. This means that if the two product system energy totals differ by more than 2.1%, there is a 95% confidence level that the difference is significant. That is, if 100 independent studies were conducted (in which new data samples were drawn from the same population and the study was conducted in the identical manner), then 95 of these studies would find the energy values for the two product systems to differ by more than 2.1%.

The previous discussion applies only to a hypothetical and highly idealized framework to which statistical mathematics apply. LCI data differ from this in some important ways. One is that the 40 or so numbers that are added together for a final energy value of a product system are of widely varying size and have different variances. The importance of this is that large numbers contribute more to the total variance of the result. For example, if 20 energy units and 2,000 energy units are added, the sum is 2,020 energy units. If the standard deviation of the smaller value is 30% (or 6 units), the variance is 6^2 = 36. If the standard deviation of the larger number is 10% (or 200), the variance is 200^2 = 40,000. The total variance of the sum is 36 + 40,000 = 40,036, leading to a standard deviation in the sum of $\frac{\sqrt{(40036)}}{2020}$ = 9.9%. Clearly, the variance in the result is much more greatly influenced by larger numbers. In a set of LCI energy data, standard deviations may range from 10% to 60%. If a large number has a large percentage standard deviation, then the sum will also be more uncertain. If the variance of the large number is small, the answer will be more certain. To offset the potential problem of a large variance, Franklin Associates goes to great lengths to increase the reliability of the larger numbers, but there may simply be inherent variability in some numbers which is beyond the researchers' control.

If only a few numbers contribute most of the total energy in a system, the value of $\Delta\%$ goes up. This can be illustrated by going back to the formula for $\Delta\%$ and calculating examples for n = 5 and 10. From statistical tables, the values for $t_{.025}$ are 2.78 for n = 5, and 2.26 for n = 10. Referring back to the hypothetical two-product data set with s% = 30% *for each entry*, the corresponding values for $\Delta\%$ are 24% for n = 5 and 9.6% for n = 10. Thus, if only 5 numbers out of 40 contribute most of the energy, the percent *difference* in the two product system energy values must increase to 24% to achieve the 95% confidence level that the two values are different. The minimum difference decreases to 9.6% if there are 10 major contributors out of the 40 energy numbers in a product system.

CONCLUSIONS

The discussion above highlights the importance of sample size, and of the variability of the sample. However, once again it must be emphasized that the statistical analysis does not apply to LCI data. It only serves to illustrate the important issues. Valid standard deviations cannot be calculated because of the failure of the data to meet the required statistical formula assumptions. Nevertheless, it is important to achieve a maximum sample size with minimum variability in the data. Franklin Associates examines the data, identifies the large values contributing to a sum, then conducts more intensive analysis of those values. This has the effect of increasing the number of data points, and therefore decreasing the "standard deviation." Even though a calculated standard deviation of 30% may be typical for Franklin Associates' LCI data, the actual confidence level is much higher for the large values that control the variability of the data than for the small values. However, none of this can be quantified to the satisfaction of a statistician who draws conclusions based upon random sampling. In the case of LCI data, it comes down to a matter of professional judgment and experience. The increase in confidence level resulting from judgment and experience is not measurable.

It is the professional judgment of Franklin Associates, based upon over 25 years of experience in analyzing LCI data, that a 10% rule is a reasonable value for $\Delta\%$ for stating results of product system energy totals. That is, if the energy of one system is 10% different from another, it can be concluded that the difference is significant. It is clear that this convention is a matter of judgment. This is not claimed to be a highly accurate statement; however, the statistical arguments with hypothetical, but similar, data lend plausibility to this convention.

We also conclude that the weight of postconsumer solid waste data can be analyzed in a similar way. These data are at least as accurate as the energy data, perhaps with even less uncertainty in the results. Therefore, the 10% rule applies to postconsumer solid waste weight. However, we apply a 25% rule to the solid waste volume data because of greater potential variability in the volume conversion factors.

Air and water pollution and industrial solid waste data are not included in the 10% rule. Their variability is much higher. Data reported by similar plants may differ by a factor of two, or even a factor of ten or higher in some cases. Standard deviations may be as high as 150%, although 75% is typical. This translates to a hypothetical standard deviation in a final result of 12%, or a difference of at least 25% being required for a 95% confidence of two totals being different if 10 subsystems are major contributors to the final results. However, this rule applies only to single emission categories, and cannot be extended to general statements about environmental emissions resulting from a single product system. The interpretation of environmental emission data is further complicated by the fact that not all plants report the same emission categories, and that there is not an accepted method of evaluating the relative importance of various emissions.

It is the intent of this appendix to convey an explanation of Franklin Associates' 10% and 25% rules and establish their plausibility. **Franklin Associates' policy is to consider product system totals for energy and weight of postconsumer solid waste weight to be different if there is at least a 10% difference in the totals. Otherwise, the difference is considered to be insignificant. In the detailed tables of this report there are many specific pollutant categories that are variable between systems. For the air and waterborne emissions, industrial solid waste, and postconsumer solid waste volume, the 25% rule should be applied.** The formula used to calculate the difference between two systems is:

$$\% \text{ Diff} = \left(\frac{x-y}{\frac{x+y}{2}} \right) \text{ X } 100,$$

where x and y are the summed totals of energy or waste for two product systems. The denominator of this expression is the average of the two values.

APPENDIX B

ALTERNATIVE SCENARIO FOR POSTCONSUMER RECYCLED CONTENT OF RPET

In today's market, the available sources of RPET feedstock for food-grade RPET can contain varying percentages of industrial and postconsumer (PC) recycled material. In the main body of the report, the RPET is modeled as 100% PC resin, which is the view of the future. Currently, food grade RPET with 50% postconsumer/50% postindustrial recycled content is readily obtainable. This appendix presents results for RPET SMX cups made with a 50/50 mix of PC and industrial recycled content. These cups will be referred to throughout this appendix as "50% PC."

In life cycle methodology, material production and disposal burdens are allocated among the useful lives of a given quantity of material. Because postindustrial material has not yet been used in a completed product with a useful life, all material production burdens for industrial scrap are allocated to the product that uses the scrap as input, e.g., the SMX cup. Therefore, the results for RPET SMX cups increase when postindustrial content replaces postconsumer content.

This appendix presents results for two scenarios for 100% RPET SMX cups with 50% PC recycled content. The results shown in the first part of this appendix are for a scenario in which cups are disposed after use. Just as in the main report, results are presented using two different allocation scenarios for the PC recycled content of the material. In each figure, results are shown for both the 100% PC RPET cup and the 50% PC RPET cup. The figures in this appendix do not include secondary packaging.

Flow diagrams illustrating how the two recycling allocation methodologies apply to each RPET SMX cup scenario are provided in Appendix C.

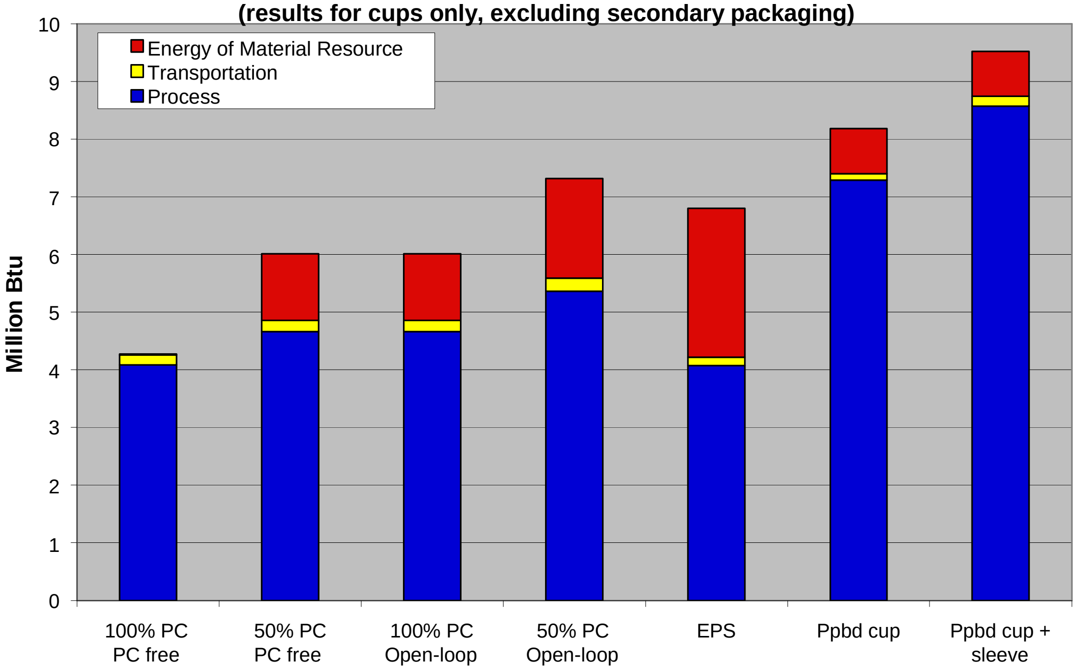
ENERGY

Total energy requirements for 100% PC RPET cups, 50% PC RPET cups, and EPS and paperboard cups are shown in Figure B-1. Comparison of the 100% PC and 50% PC results for each recycling scenario shows that the energy burdens are higher for the cup with postindustrial content, since the postindustrial material carries in the energy burdens for its production.

The figure also shows that the energy results for the 50% PC cup using PC free allocation are the same as the energy results for the 100% PC cup using open-loop allocation. This can be explained as follows: For the 50% PC cup using PC free allocation, the total energy is calculated based on 50% postconsumer material coming in with no virgin production burdens but with full collection and reprocessing burdens, and 50% postindustrial material coming in with full material production burdens. For the 100% RPET cup in the allocated scenario, the total number of useful lives for the material is 2, so the total quantity of postconsumer input material is assigned half (50%) of the virgin production burdens as well as half of the burdens for collection and reprocessing of the postconsumer material. (See Appendix C Figures C-3 and C-5 for flow diagrams illustrating these scenarios.)

Total energy requirements for the RPET SMX cups are lower than or not significantly different from EPS cups. RPET SMX cups have lower energy than paperboard cups with and without sleeves, except for 50% PC open-loop RPET cups, which are not significantly different from paperboard cups without sleeves.

Figure B-1. Total Energy for 10,000 Cups:
Sensitivity to SMX Cup PC Recycled Content
(results for cups only, excluding secondary packaging)



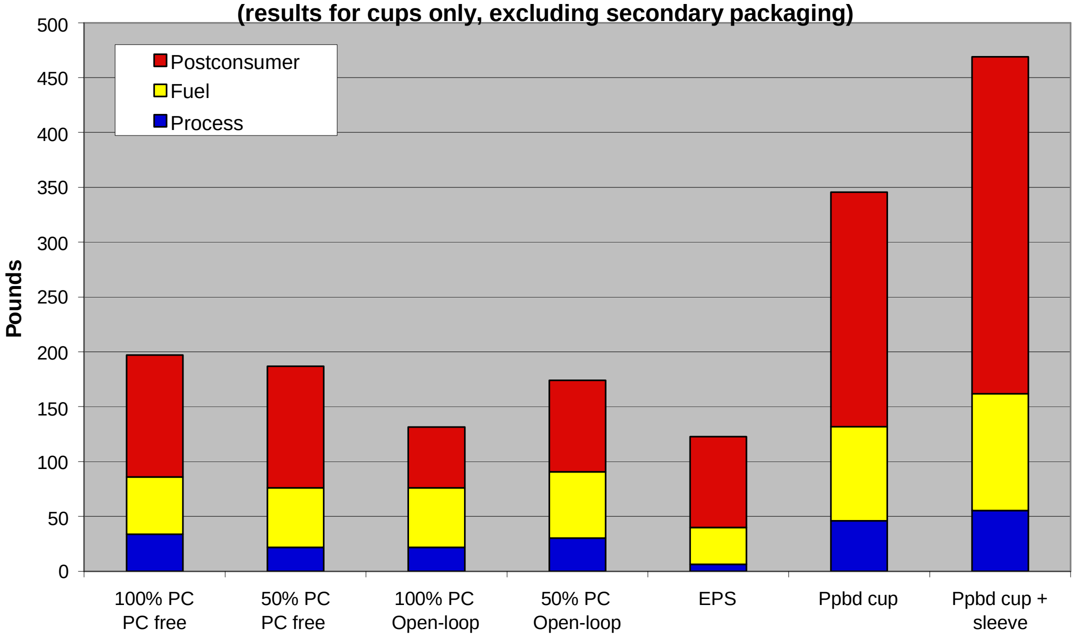
For total energy, a percent difference of 10% or greater between 2 systems' results is considered significant.

SOLID WASTE WEIGHT

Figure B-2 presents comparative results for the weight of solid waste for 100% PC RPET cups, 50% PC RPET cups, and EPS and paperboard cups. The results for the two 50% PC RPET cup scenarios fall between the results for the two 100% PC RPET scenarios. For the PC free recycling method, the 50% PC RPET has slightly less solid waste than the 100% PC RPET because there are more solid wastes associated with recovery and processing of postconsumer scrap compared to industrial scrap.

Both 50% PC RPET scenarios show higher total weight of solid waste compared to the EPS cup and lower total solid waste by weight compared to paperboard cups with and without sleeves.

Figure B-2. Total Weight of Solid Waste for 10,000 Cups: Sensitivity to SMX Cup PC Recycled Content (results for cups only, excluding secondary packaging)



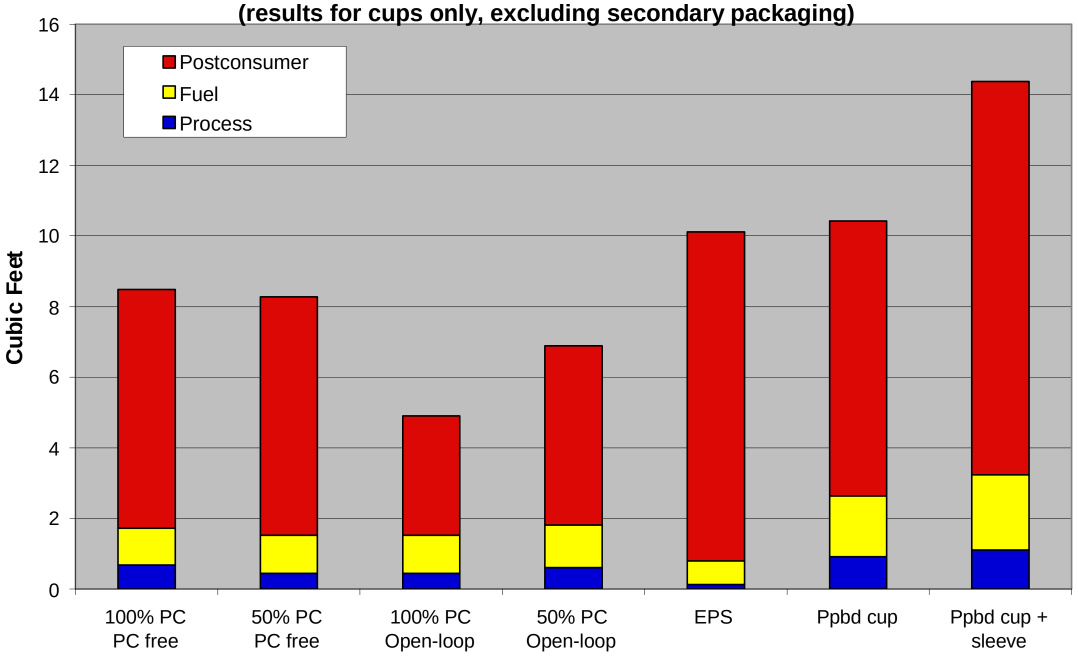
For solid waste, a percent difference of 25% or greater between 2 systems' overall results is considered significant.
For the weight of postconsumer solid waste only, a percent difference of 10% is considered significant.

SOLID WASTE VOLUME

The total volume of solid waste for production and disposal of 10,000 cups is presented in Figure B-3 for 100% PC RPET cups, 50% PC RPET cups, and EPS and paperboard cups. When landfill densities are used to convert the weights of solid waste to volume, the low density of the EPS cup increases its solid waste volume relative to the SMX and paperboard cups, which compact more densely.

When the PC free recycling methodology is used, the total solid waste for RPET SMX cups at 100% and 50% PC content are not significantly different from the EPS and paperboard cups without sleeves. For the open-loop recycling methodology, both the 100% PC and 50% PC RPET SMX cups have significantly lower volume than the EPS and paperboard cups.

Figure B-3. Total Volume of Solid Waste for 10,000 Cups: Sensitivity to SMX Cup PC Recycled Content (results for cups only, excluding secondary packaging)



For solid waste volume, a percent difference of 25% or greater between 2 systems' results is considered significant.

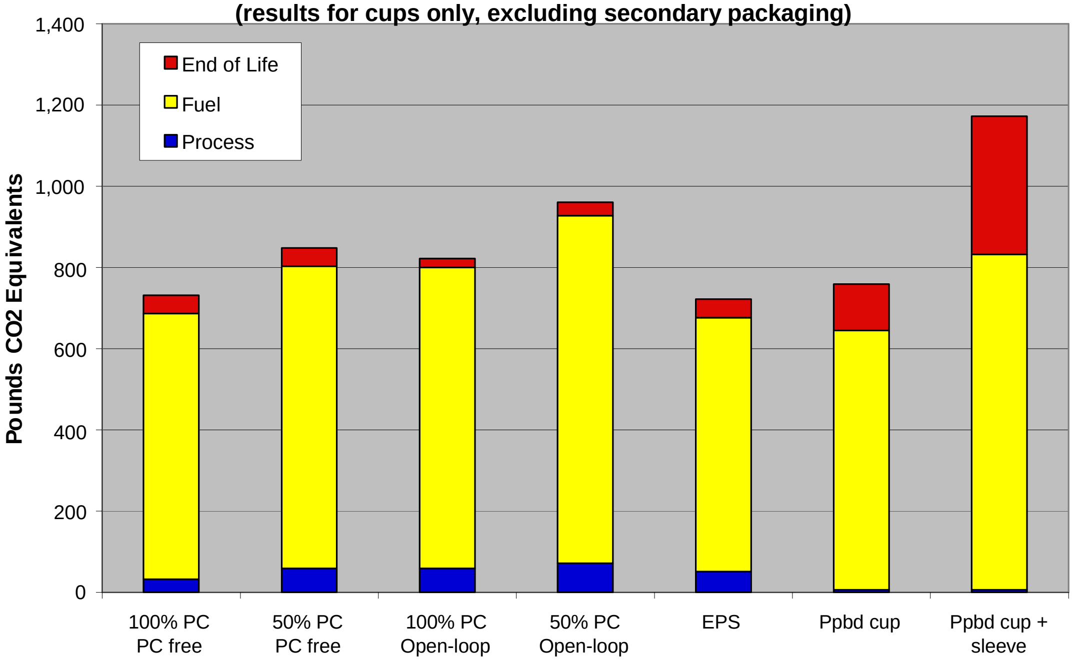
GLOBAL WARMING POTENTIAL

Figure B-4 shows total global warming potential for the RPET SMX cup scenarios and EPS and paperboard cups. The end-of-life GWP for paperboard items in Figure B-4 represents a scenario in which the degree of decomposition for paperboard products was modeled at 50 percent of the maximum degree of decomposition in landfill simulation experiments, and landfill gas management was based on the national average composite scenario.

Of the RPET cup scenarios, the 50% PC RPET open-loop scenario has the highest GWP because it carries a higher share of virgin material production GWP burdens (full GWP burdens for the 50% industrial scrap content plus half of the virgin burdens for the 50% postconsumer recycled content, or 50% + 50%/2 = 75% virgin material burdens).

The differences in total GWP for the SMX cups and the other cups are generally not significant. Exceptions are the 50% PC RPET cup using the open-loop recycling method, which has higher total GWP than the EPS cup, and the paperboard cup with sleeve, which is higher than all the RPET SMX scenarios except 50% PC open-loop. It should be noted that end-of-life GWP accounts for a large share of the total GWP for the paperboard cup with sleeve, and end-of-life emissions are more uncertain than process and fuel-related GWP. This is because the end-of-life GWP estimates include projections and assumptions about the decomposition of paperboard in landfills and the management of landfill gas, which can vary greatly depending on conditions at individual landfills.

Figure B-4. Total Global Warming Potential for 10,000 Cups: Sensitivity to SMX Cup PC Recycled Content (results for cups only, excluding secondary packaging)



For GWP, a percent difference of 25% or greater between 2 systems' results is considered significant.

The comparative results presented in Figures B-1 through B-4 show that there are differences in the environmental burdens for RPET material depending on the relative percentages of postconsumer and postindustrial content. Higher use of postconsumer material means that less virgin PET burdens are allocated to the RPET, and thus to the RPET SMX cup.

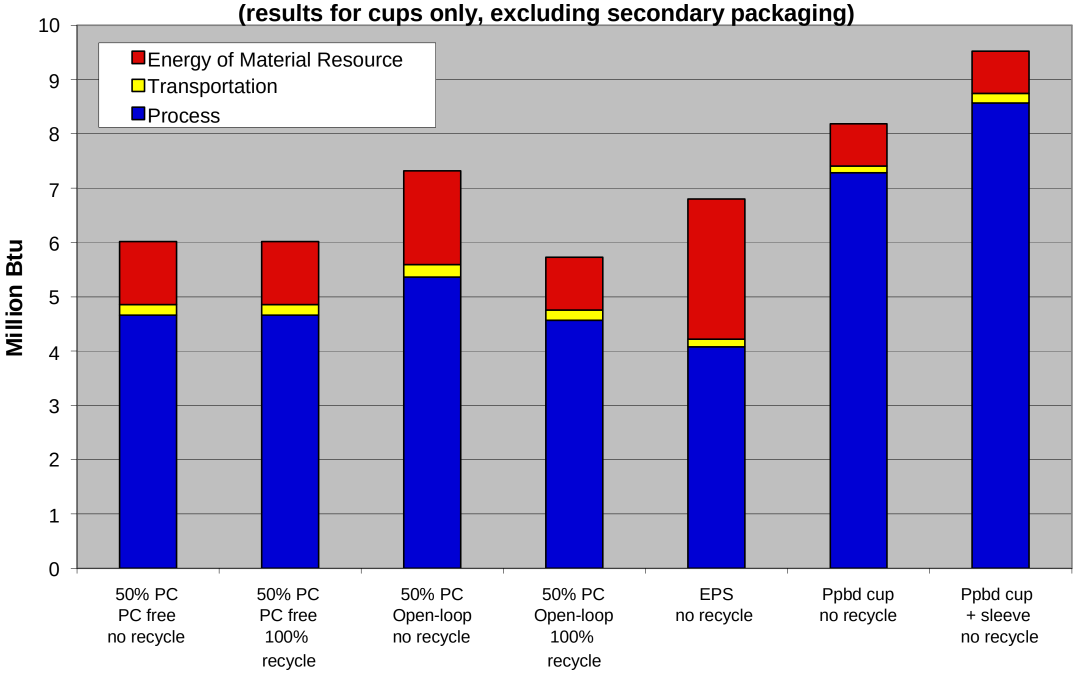
RESULTS FOR POSTCONSUMER RECYCLING OF 50% PC RPET CUPS

The potential for recycling RPET SMX cups is discussed in the main body of the report in the section "RPET SMX Cup Recycling Scenario." Results are shown in Figures B-5 through B-8 for a scenario in which the 50% PC RPET cups are recycled at end of life. In each figure, the cup recycling scenario is compared to the scenario in which the cups are disposed at end of life. The explanation of how results change due to end-of-life recycling for the two recycling methodologies (PC free and open-loop recycling) is the same as described in the main report for 100% PC RPET SMX cups and is not repeated here.

For the **PC free** recycling methodology, Figures B-5 through B-8 show that the 50% PC RPET cup at 100% recycling (second bar displayed in each figure) produces less solid waste by weight and by volume than the EPS and paperboard cups at 0% recycling. The recycled RPET cup has lower energy compared to the paperboard cup (with and without sleeve), but is not significantly different from the EPS cup for energy.

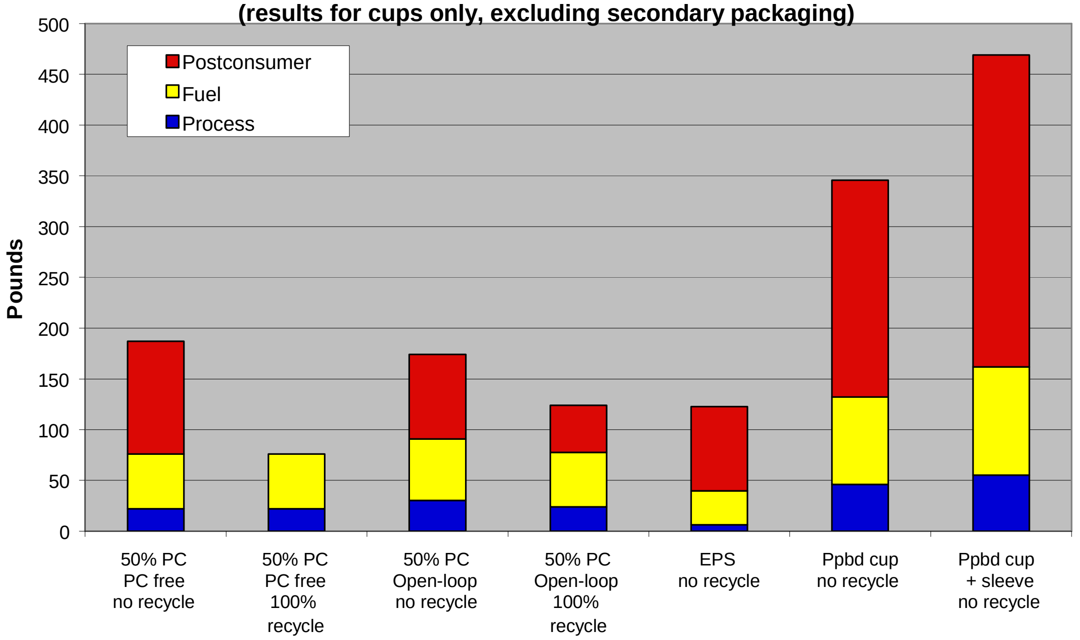
For the **open-loop** recycling methodology, Figures B-5 through B-8 show that the 50% PC RPET cup at 100% recycling (fourth bar displayed in each figure) has lower energy and lower solid waste by weight and by volume compared to paperboard cups with and without sleeves. The recycled RPET cup has lower total energy and solid waste volume compared to EPS cups, but is not significantly different in total weight of solid waste.

Figure B-5. Total Energy for 10,000 Cups:
Sensitivity to 50% PC RPET SMX Cup Recycling
(results for cups only, excluding secondary packaging)



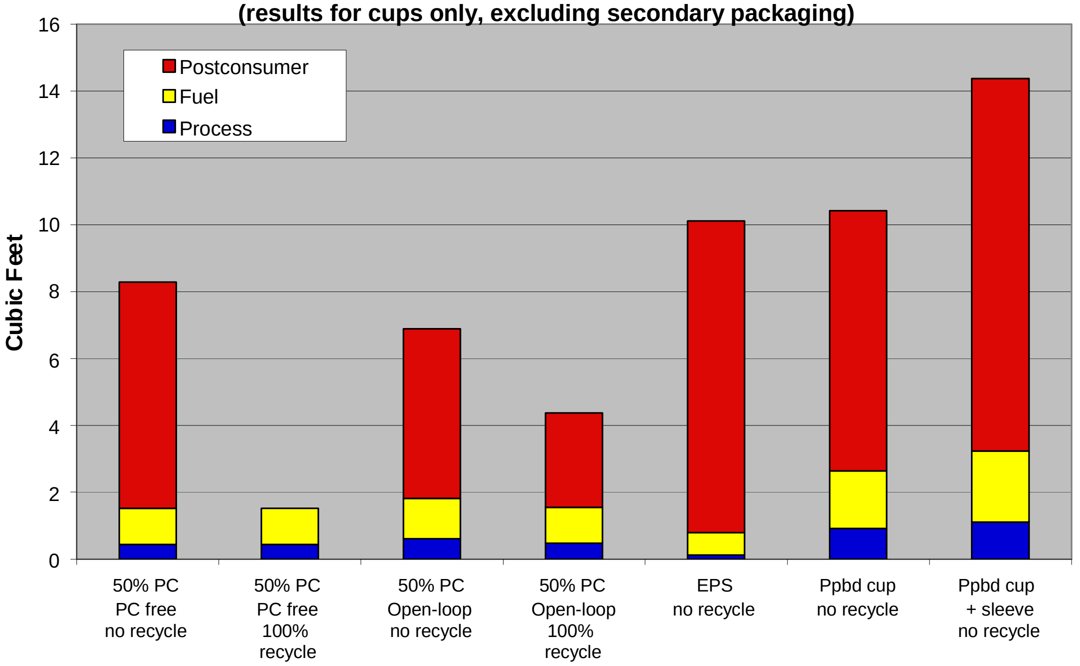
For total energy, a percent difference of 10% or greater between 2 systems' results is considered significant.

Figure B-6. Total Weight of Solid Waste for 10,000 Cups: Sensitivity to 50% PC RPET SMX Cup Recycling (results for cups only, excluding secondary packaging)



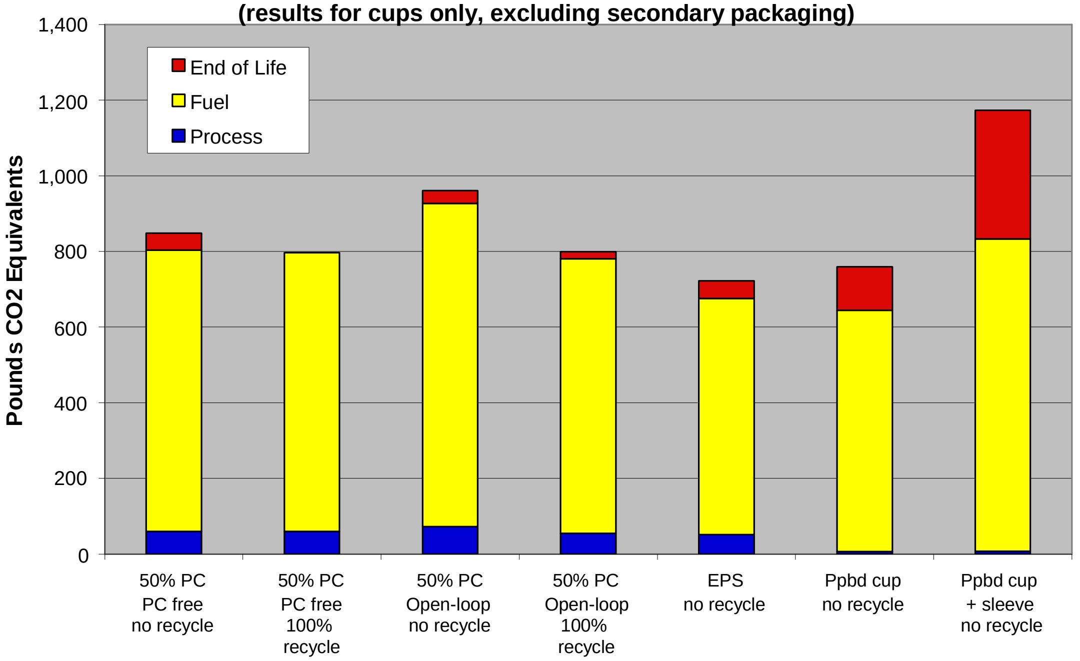
For solid waste, a percent difference of 25% or greater between 2 systems' overall results is considered significant.
For the weight of postconsumer solid waste only, a percent difference of 10% is considered significant.

Figure B-7. Total Volume of Solid Waste for 10,000 Cups: Sensitivity to 50% PC RPET SMX Cup Recycling (results for cups only, excluding secondary packaging)



For solid waste volume, a percent difference of 25% or greater between 2 systems' results is considered significant.

Figure B-8. Total Global Warming Potential for 10,000 Cups: Sensitivity to 50% PC RPET SMX Cup Recycling (results for cups only, excluding secondary packaging)



For GWP, a percent difference of 25% or greater between 2 systems' results is considered significant.

APPENDIX C

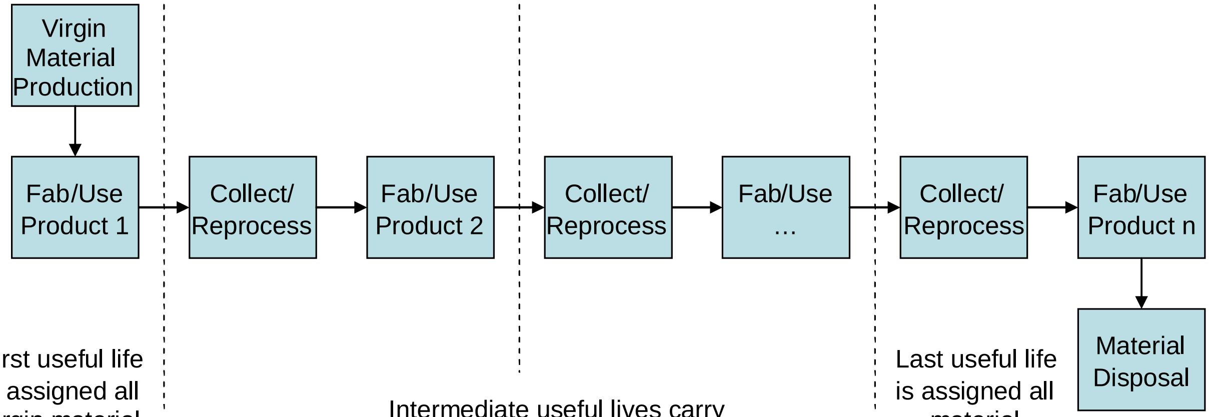
RECYCLING METHODOLOGY FLOW DIAGRAMS

To assist the reader in understanding allocations under the two recycling methodologies used in this analysis, flow diagrams are provided in this appendix. The first diagram, Figure C-1, depicts the postconsumer "free" methodology, and the second diagram, Figure C-2, describes the open-loop allocation methodology.

The last three diagrams illustrate how these methodologies are applied to the RPET SMX cup scenarios in this analysis:

- Figure C-3: 100% postconsumer RPET cup system at 0% recycling
- Figure C-4: 100% postconsumer RPET cup system at 100% recycling
- Figure C-5: 50% postconsumer/50% postindustrial RPET cup system at 0% recycling.

Figure C-1. Postconsumer “Free” Recycling Methodology
(total useful lives = n)



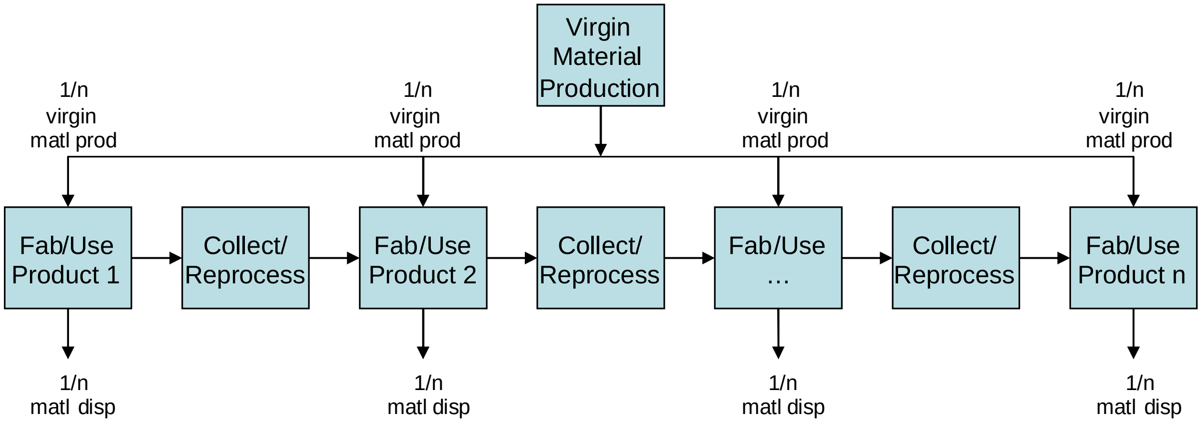
First useful life is assigned all virgin material production burdens.

Intermediate useful lives carry collection and reprocessing burdens, but no share of virgin production burdens or material disposal burdens.

Last useful life is assigned all material disposal burdens.

Each useful life carries its own product fabrication and use burdens.

Figure C-2. Open-loop Allocation Recycling Methodology
(total number of useful lives = n)

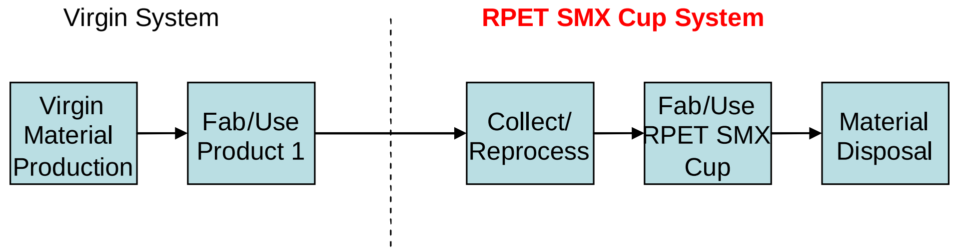


This method distributes the virgin production burdens and final disposal burdens over all useful lives of the material. Each useful life is allocated an equal share (1/n) of virgin material production burdens *and* material disposal burdens. Each useful life carries its own product fabrication and use burdens.

The total number of collection/reprocessing cycles is n-1, so total collection/reprocessing burdens allocated over all useful lives = (n-1)/n allocated to each useful life.

Figure C-3. 100% POSTCONSUMER RPET SMX CUP WITH NO RECYCLING

Postconsumer “Free”



Open-loop Allocation, n = 2
1/n = 1/2

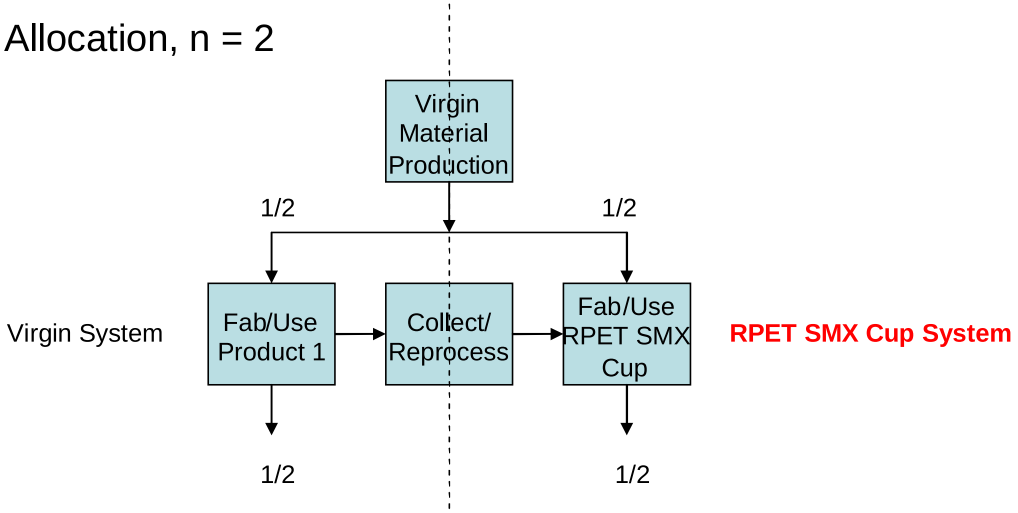
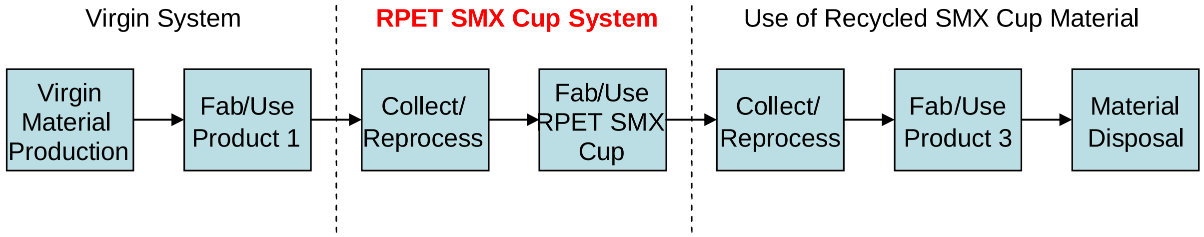


Figure C-4. 100% POSTCONSUMER RPET SMX CUP RECYCLED AFTER USE

Postconsumer “Free”



Open-loop Allocation, n = 3
1/n = 1/3

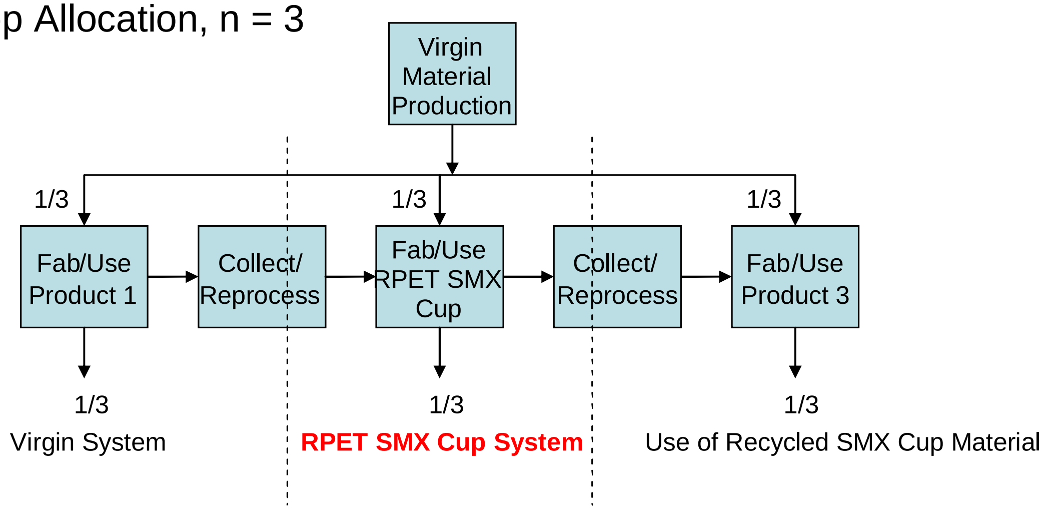
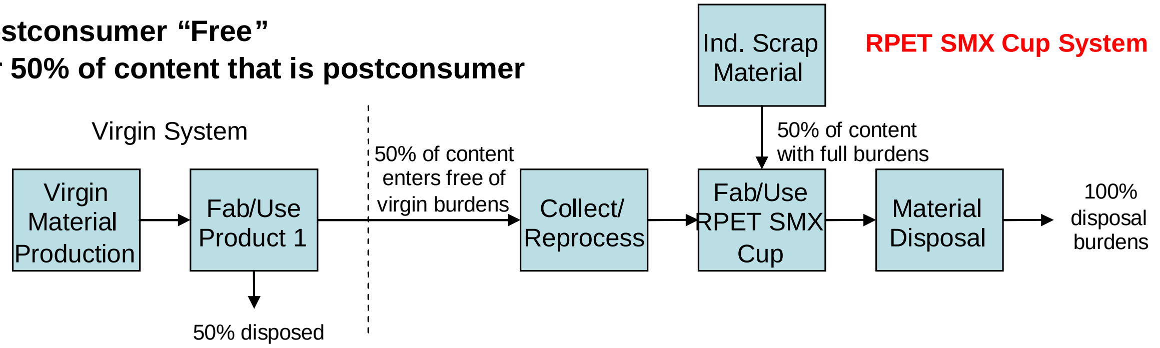


Figure C-5. 50% POSTCONSUMER RPET SMX CUP WITH NO RECYCLING

Postconsumer "Free"
for 50% of content that is postconsumer



Ind. Scrap Material

RPET SMX Cup System

Virgin System

Virgin Material Production

Fab/Use Product 1

50% disposed

50% of content enters free of virgin burdens

Collect/ Reprocess

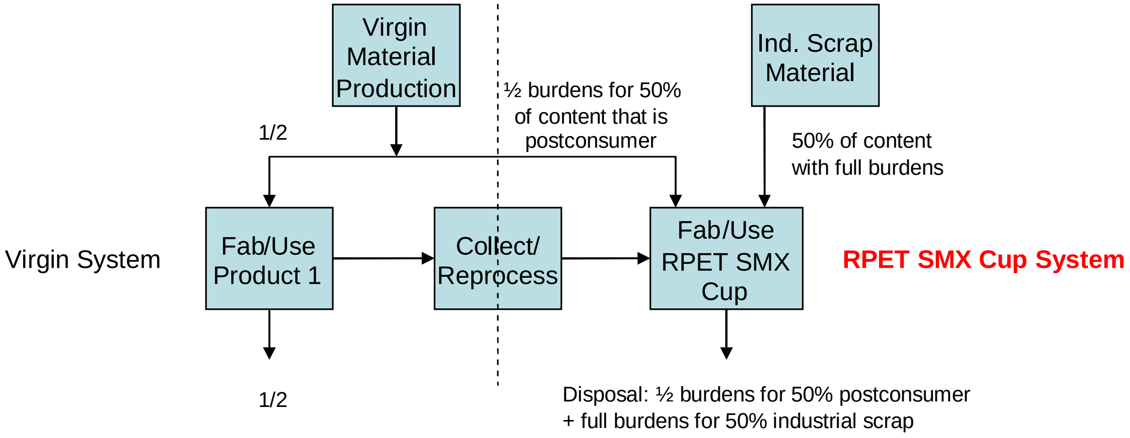
50% of content with full burdens

Fab/Use RPET SMX Cup

Material Disposal

100% disposal burdens

Open-loop Allocation, n = 2
1/n = ½ burdens for 50% of content that is postconsumer



Virgin Material Production

Ind. Scrap Material

1/2

½ burdens for 50% of content that is postconsumer

50% of content with full burdens

Virgin System

Fab/Use Product 1

Collect/ Reprocess

Fab/Use RPET SMX Cup

RPET SMX Cup System

1/2

Disposal: ½ burdens for 50% postconsumer
+ full burdens for 50% industrial scrap

PEER REVIEW

After completion of the LCI and prior to public release, the full LCI report was submitted to Dr. David Allen of the University of Texas at Austin for peer review. Dr. Allen's review and Franklin's response to each comment are attached.

A brief bio of Dr. Allen summarizing his experience and qualifications is attached at the end of this report.

PEER REVIEW

of

LIFE CYCLE INVENTORY OF 16-OUNCE DISPOSABLE HOT CUPS
Final Report

Prepared for

FRANKLIN ASSOCIATES, A Division of ERG

By

Dr. David Allen
University of Texas

December 28, 2008

SUMMARY

At the request of the Franklin Associates, a peer review was conducted of a life cycle inventory (LCI) on disposable hot cups by an external expert familiar with LCI. The reviewer was provided the Executive Summary, a report and some appendices to review. In addition, the report made extensive use of a previous LCI done for the Polystyrene Packaging Council, and this LCI was available through the American Chemistry Council's web site. The disposable hot cup LCI was reviewed against the following six criteria:

- 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?

The calculations, assumptions employed, and data analysis methods were, with minor exceptions, clear, technically sound, and consistent with ISO 14040 series documents. The sources of data were generally clearly identified and representative. Although the calculations were not replicated, the analyses yielded results that seemed reasonable. Overall, the case studies met the high professional standards that life cycle assessment practitioners have come to expect from Franklin Associates.

Areas where additional explanations or calculations would be beneficial, and where the study did not conform to ISO 14044 requirements are summarized below.

Comments and Suggestions

- A 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." The reports strongly imply that the case study goals are to make comparative assertions; however, this goal is not unambiguously stated.
  Response: Clarifying language has been added to the Intended Use section of the report.
- A requirement of ISO 14044:2006 Section 6.3 is that an external review should consist of at least 3 panel members. This review is being conducted by a single external expert.
  Response: Section 6.1 of ISO 14044 states: "In order to decrease the likelihood of misunderstandings or negative effects on external interested parties, a panel of interested parties shall conduct critical reviews on LCA studies where the results are intended to be used to support a comparative assertion intended to be disclosed to the public." *A panel peer review (as*

opposed to a single reviewer) is only required by ISO for studies intended for public comparative assertions. There is some room for interpretation of ISO's definition of "comparative assertion", which is defined in ISO 14044 section 3.6 as "environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function." *Franklin Associates interprets this definition to mean a* **general, qualitative claim of superiority or equivalence,** *rather than a* **specific, quantified statement** *that is clearly supported by the study results. Under this interpretation, "The LCA shows that System A is environmentally preferable to System B" would be a comparative assertion, while "System A requires 22 percent less energy over its life cycle compared to System B" would not. When making comparative statements about alternative systems, Franklin Associates is careful to make specific, quantified statements that are clearly supported by the study results. No claims about environmental superiority are made in this report. Furthermore, this analysis is intended as a benchmarking study to evaluate a prototype RPET cup against average competing disposable cups. The SMX RPET cups are not currently in production and are not in a position to compete in the marketplace with other disposable cups, minimizing any potential for this analysis to have negative effects on external interested parties. Language clarifying the purpose and intended use of the study has been added to the report.*

- The choice of cup weights can significantly affect study results. Different manufacturers can produce cups, designed to hold the same volumes, which have different weights, and even for a single manufacturer, cup weights can vary with time. The report would be improved if a range of cup weights were used in the analyses, and if the report gave information on the time frame and geographical area over which the cup weight data were collected.
  Response: It is agreed that the choice of cup weights can affect study results and conclusions. This analysis was intended as a benchmarking study to evaluate a prototype RPET SMX cup against commonly available disposable cups. Language has been added to the report to clarify this. For an initial benchmark of the prototype cup, it was considered sufficient to compare to average weight products available in the marketplace using product weights from the published peer-reviewed PSPC study. A sentence has been added to the report to note that the average product weights in the PSPC study were based on samples obtained in 2002 from North American manufacturers.
- The study assumes that carbon dioxide used in the cup forming process for the RPET SMX product escapes, but notes that in the future, capture and recycle of these emissions could occur. It would be useful to present a sensitivity analysis that examines the impact of this assumption. A conclusion on page 2-27 suggests that these emissions are small, but more explicit presentation of these data would improve the transparency of the report.

Response: On page 2-20 it is stated that the "total process emissions for the RPET SMX cup, including these carbon dioxide emissions, account for only about 5 percent of the total process and fuel-related GWP for the RPET SMX cup system." This gives the reader a better idea of the magnitude of these emissions without revealing potentially sensitive data about the SMX process.

- In the primary scenario used in the study, the material used in the RPET is modeled as 100% post-consumer with a total of 3 uses (page 1-9). This analysis assumes an extensive food-grade RPET stream will be available, but RPET SMX cups are not yet in production (page 1-12). It is difficult to justify an assumption that relies on the emergence of an extensive recycled content stream that does not currently exist. A sensitivity analysis was performed for RPET SMX cups made with a "more common" (page 2-3) 50/50 mix of post-consumer and industrial recycled content, to partially address this concern, however, even this scenario assumes a significant recycled product stream. The study would be improved with the inclusion of a sensitivity analysis based on a 50/50 mix of virgin and industrial recycled content RPET SMX cups.
  Response: As described in previous responses, this analysis was intended to provide a benchmark of a prototype SMX RPET cup compared to commonly used alternative disposable cups. MicroGREEN Polymers confirms that RPET SMX cups are not being made from a 50% virgin/50% industrial scrap mix, and that their suppliers produce a substantial supply of RPET film with at least 50% guaranteed postconsumer content (240 tons per year).
- On page 1-7, it is noted that a variety of allocation procedures have been used in the analyses, with decisions on which allocation procedure to use made on a case-by-case basis. The transparency of the report would be improved by the inclusion of a Table summarizing the allocation methods used in calculations that lead to the largest contributions to the inventory.
  Response: A table summarizing the allocation procedures and the cup systems affected by each has been added to the Methodology chapter.
- In this study, no fuel-energy equivalent (Energy of Material Resource, EMR) is assigned to combustible materials such as wood that are not major fuel sources in the United States. However, in this study wood energy is also included as process energy, and a credit is given for wood combustion at end of life. This is not consistent, and this inconsistency is noted on page 1-8. So, while the report is transparent on this issue, it is inconsistent in its handling of the EMR of wood-based fuels.
  *Response: As clearly described in the Methodology chapter, EMR is a method of accounting for the depletion of resources whose predominant use is as for energy; EMR is not intended to account for the energy content of **all** raw materials removed from the natural environment. On this basis, it is not inconsistent to report actual energy derived from wood (or its products) yet not assign EMR to the energy content of the wood that becomes part of the product. Within the geographic boundaries for this*

study, forest resources are harvested for use as a material. If not used for paperboard production or other material uses, the trees would be not be harvested for fuel; thus, while wood wastes or products are sometimes utilized as an energy source, material use of wood in a product is not considered a diversion from its use as an energy resource. Furthermore, the inclusion of EMR for wood would not change energy conclusions, since this would increase the energy requirements for the paperboard cup system, which already has higher energy requirements compared to the RPET and EPS cups.

- On page 1-10, data should be cited to justify the assumption of a 95% recycling rate for corrugated packaging.

  Response: This is an estimate by Franklin Associates based on the types of establishments where the corrugated cases of cups are likely to be emptied. The current overall recycling rate for corrugated packaging is 73.6 percent, as published in the U.S. EPA's Municipal Solid Waste 2007 Facts & Figures. This is the composite rate for the total supply of postconsumer corrugated generated from residential and municipal sources. The corrugated packaging in this analysis is based on cases containing 1000 cups. Cases of this size are likely to be unpacked at stores where cups are sold by the sleeve, or at restaurants or foodservice operations that go through large volumes of disposable products on a daily basis. Both of these types of establishments would need to manage large volumes of empty corrugated packaging for cups and other products on a regular basis, so it is likely that these facilities would recover the material as a source of income rather than incurring costs for disposal. Using a lower corrugated recycling rate (e.g., between the national average 73.6 percent and the 95 percent used in this analysis) would result in a small increase in the environmental burdens per pound for corrugated packaging used for all cup systems. The net effect on overall system results would be largest for the cup systems that use the most corrugated (i.e., the EPS cup and the paperboard cup with sleeve).
- On page 1-16, the study states that "estimates of the end results of landfilling and WTE combustion are limited to global warming effects". This incorrect. As noted on pages 1-8 and 1-9, WTE combustion is also accounted for in the energy analyses.

  Response: The explanation has been revised to note that energy recovery is also included.
- In the Tables in Chapter 2 (e.g., Table 2-2), it is not clear why comparisons are done based on Total Energy, rather than Net Energy. It is also not clear whether the Figures in Chapter 2 are reporting Total or Net Energy.

  Response: Total Energy and Net Energy (reflecting adjustments for energy credits) are shown separately both for transparency and because of differences in confidence in the results. As described in the End of Life Methodology section of Chapter 1, the end-of-life energy credits are more uncertain than other energy values. The end-of-life energy credit *calculations include assumptions about the energy released from combustion of postconsumer cups and packaging, and the efficiency in converting combustion energy to useful electricity. For paper-based cups, sleeves, and packaging, there are additional assumptions about the amount and fate of methane produced from landfill decomposition and the useful electricity produced from combustion of captured landfill gas that is burned with energy recovery. Because the energy recovery adjustments are small in comparison to the production energy requirements, comparative results for net energy are very similar to total energy, as can be seen in the net energy percent differences that have been added to Table 2-2.*

In response to the reviewer's question about the Chapter 2 Figures, these show Total Energy results, as described in the Figure titles.

- To improve the report's transparency, the criteria for concluding that there are significant differences between product systems (e.g., 10% difference for energy, 25% difference for waste volume) should be indicated in the Figures or the Figure captions reporting the results and in summaries of key conclusions.

  Response: The criteria have been added to the report Figures and summaries of key conclusions at the end of each chapter, as suggested.
- On page 2-17, it is noted that the global warming potentials (GWPs) used in this work are not consistent with the most recent IPCC reports, but were chosen to be consistent with international reporting standards. The report would be improved if a sensitivity analysis were performed, using the new IPCC GWPs for the portions of the inventory where this is possible.

  Response: The majority of the GWP is from CO_2*, which is assigned the reference value of 1 in all IPCC reports; however, the contribution to total GWP from other substances such as methane and nitrous oxide is affected by the choice of IPCC report used as the source of GWP factors. A paragraph has been added to the GWP section discussing the effect of using the most recent IPCC GWPs as published in the 2007 IPCC report.*
- On page 2-19, paragraph 2, line 5, "currently released with recovery" should be "currently released without recovery."

  Response: This has been corrected.
- In Appendix B, the data in some of the Figures do not appear to match the data in the main body of the report. For example, in Figure B-1, the data for the EPS system does not appear to be consistent with data in Figure 2-1. Similar inconsistencies (but none that impacted the conclusions of the report) were noted in other Figures in Appendix B.

  Response: Appendix B presents results only for cups, while the results in Chapter 2 include packaging. The Figure titles state whether the results shown are for cups and packaging or for cups, and this is also described in paragraph 3 of Appendix B. However, to make the distinction clearer, additional wording explicitly noting the exclusion of secondary packaging has been added to the titles of the Appendix B figures.

David T. Allen

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.