LIFE CYCLE INVENTORY OF FOAM POLYSTYRENE, PAPER-BASED, AND PLA FOODSERVICE PRODUCTS

Prepared for

THE PLASTIC FOODSERVICE PACKAGING GROUP

by

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ABBREVIATIONS

CO_2 eq: Carbon dioxide equivalents

EMR: Energy of material resource

EOL: End of life

EPS: Expanded polystyrene

GHG: Greenhouse gas

GPPS: General purpose polystyrene

GWP: Global warming potential

IPCC: Intergovernmental Panel on Climate Change

LDPE: Low density polyethylene

LF: Landfill

LFG: Landfill gas

MSW: Municipal solid waste

PLA: Polylactide resin

PS: Polystyrene resin (used to refer to both EPS and GPPS)

WTE: Waste to energy

EXECUTIVE SUMMARY

INTRODUCTION

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

This study is an extension of a peer-reviewed life cycle inventory (LCI) completed in 2006 for the Polystyrene Foodservice Packaging Council (PSPC), which is now known as the Plastic Foodservice Packaging Group (PFPG). Although the study is conducted as a life cycle inventory, this analysis includes the evaluation of the impact category global warming potential (GWP) using 100-year GWP factors from the Intergovernmental Panel on Climate Change (IPCC).

STUDY GOAL AND INTENDED USE

The goal of this study is to extend the scope of the 2006 PSPC LCI to include the following additions:

1. Production and disposal of available PLA products corresponding as closely as possible to the average weight foodservice products in the original LCI,
2. Modeling of the carbon footprint implications of landfilling and waste-to-energy (WTE) incineration of the average weight foodservice products from the original study and the PLA products,
3. Addition of water use to the life cycle inventory results.

The primary intended use of the study results is to provide PFPG with more complete information about the environmental burdens and greenhouse gas impacts from the life cycle of disposable foodservice products. Because this study is based primarily on **average weight** polystyrene foam and paperboard products from the original PSPC study, plus limited availability of PLA product samples, **the results of this study should *not* be used to draw general conclusions about comparative results for the full range of product weights available in each product category**.

Because the study will be made publicly available on the ACC website, the completed report has been peer reviewed prior to release. The peer review report is included as an appendix to this report.

SYSTEMS STUDIED

The following foodservice product categories are included in the analysis:

- 16-ounce hot cups (EPS foam, poly-coated paperboard with and without a corrugated sleeve, PLA-coated paperboard with and without a corrugated sleeve)
- 32-ounce cold cups (EPS foam, poly-coated paperboard, wax-coated paperboard, solid PLA)
- 9-inch high-grade plates (GPPS foam, poly-coated paperboard, bleached molded pulp, solid PLA)
- Sandwich-size clamshells (GPPS foam, corrugated paperboard, solid PLA)

EPS and GPPS foam products have different structures because of differences in how the blowing agent is added. For EPS products, the blowing agent is incorporated into the resin bead. At product manufacture, the beads are expanded with steam, resulting in products consisting of fused expanded beads. For GPPS products, the resin delivered to the converter is solid and does not include blowing agent. The converter introduces the blowing agent into the molten resin, producing a product with a continuous foamed structure.

For the most part, the products modeled in this analysis are based on the average weight products in the 2006 PSPC study. For the new category of PLA products, a literature search was conducted for published information on weights of PLA foodservice products, and product samples were ordered from several companies.

Although the goal of the study was to model PLA products that corresponded as closely as possible with the PSPC study foodservice products, no PLA foam products were found. Therefore, for the cold cup, plate, and clamshell applications, solid PLA products are analyzed. Since the properties of PLA are not suitable for hot cups to be made entirely from PLA, in the hot cup category a 16-ounce hot cup PLA-coated paperboard hot cup is evaluated.

For the category of plates, the 2006 PSPC study analyzed plates that were categorized as heavy-duty plates. These were the heaviest and sturdiest plates available; however, information on the relative strengths of these plates was not available. This report also includes results for two lighter-weight plates from a 2009 study. The 2009 plates are in a different weight class from the heavy-duty plates from the 2006 study and should not be directly compared to the 2006 heavy-duty plates. Results for the two lighter class plates are provided for two reasons: (1) to illustrate how LCI results can vary based on the weight of the product, and (2) to present a comparison based on actual equivalent strength (since strength information was not available for the heavy-duty plates).

The product weights analyzed in this study are listed in Table ES-1, together with a brief description of the source of the weight data.

SCOPE AND BOUNDARIES

The PSPC LCI included all steps in the production of each foodservice item, from extraction of raw materials through production of the finished product. In this analysis, the evaluation of foodservice products utilizing PLA uses corresponding scope and boundaries. The modeling for PLA production begins with corn growing and continues through production of PLA resin and fabrication of PLA foodservice products.

This analysis builds upon the original 2006 study, using the average product weights from that study. The scope of this study did not include updating the full range of product weights available in the marketplace. Readers interested in results for the full range of product weights for polystyrene foam and paperboard products are encouraged to refer to the 2006 study.[1]

In the U.S., municipal solid waste (MSW) that is not recovered for recycling or composting is managed by landfilling and waste-to-energy (WTE) incineration. The relative percentages of MSW managed by these methods is approximately 80 percent by weight to landfill (LF) and 20 percent by weight to waste-to-energy (WTE) incineration.[2] For material that is disposed by WTE combustion, an energy credit is given based on the amount of each material burned, its higher heating value, and the efficiency of converting the gross heat of combustion to useful energy.

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1 "Final Peer-Reviewed Report: Life Cycle Inventory of Polystyrene Foam, Bleached Paperboard, and Corrugated Paperboard Foodservice Products." conducted by Franklin Associates, Ltd. for PSPC in March 2006. Available at http://www.americanchemistry.com/s_plastics/bin.asp?CID=1211&DID=9088&DOC=FILE.PDF

2 U.S. EPA. Municipal Solid Waste Facts and Figures 2008. Accessible at http://www.epa.gov/msw/msw99.htm.

Table ES-1. Products Modeled

16 oz Hot Cups	**grams/ item**	**Source**	**Weight ratio compared to avg PS foam product**	**Wt range in 2006 study (g)**
EPS	4.7	average weight cup from 2006 PSPC study		4.4 - 5.0
LDPE-coated Paperboard	13.3	average weight cup from 2006 PSPC study	2.8 for cup only; 4.1 for cup + sleeve	12.3 - 15.0
PLA-coated Paperboard	12.7	average wt of 16 samples from one manufacturer	2.7 for cup only; 3.9 for cup + sleeve	N/A
Unbleached Corrug Sleeve	5.8	average weight cup sleeve from 2006 PSPC study		4.1 - 7.5

32 oz Cold Cups	**grams/ item**	**Source**	**Weight ratio compared to avg PS foam product**	**Wt range in 2006 study (g)**
EPS	8.8	average weight cup from 2006 PSPC study		8.1 - 10.0
LDPE-coated Paperboard	19.8	average weight cup from 2006 PSPC study	2.2	19.8 - 23.3
Wax-coated Paperboard	31.3	average weight cup from 2006 PSPC study (one producer)	3.5	
Solid PLA 1	35.0	estimated based on weight of a 32 oz PP cup (23.3 g) and the weight ratios of samples of 24 oz PLA and PP cups produced by the same manufacturer (1)	4.0	N/A
Solid PLA 2	32.4	estimated based on the weight of 32 oz PP cup and ratio of densities of PLA and PP (2)	3.7	N/A

9-inch Heavy Duty Plates	**grams/ item**	**Source**	**Weight ratio compared to avg PS foam product**	**Wt range in 2006 study (g)**
GPPS Foam	10.8	average weight plate from 2006 PSPC study		10.4 - 11.1
LDPE-coated Paperboard	18.4	average weight plate from 2006 PSPC study	1.7	18.2 - 18.5
Solid PLA	20.7	estimated based on weight of solid PS plate samples (18 g) and the weight ratio of solid PLA and solid PS clamshells produced by the same manufacturer (3)	1.9	N/A
Molded Pulp	16.6	average weight plate from 2006 PSPC study	1.5	16.2 - 17.4

9-inch Lightweight Plates	**grams/ item**	**Source**	**Weight ratio compared to avg PS foam product**
GPPS Foam	4.7	separate 2009 study	
Competing LDPE-coated Paperboard	12.1	separate 2009 study	2.6

Sandwich-size Clamshells	**grams/ item**	**Source**	**Weight ratio compared to avg PS foam product**	**Wt range in 2006 study (g)**
GPPS Foam	4.8	average weight clamshell from PSPC study		4.4 - 5.0
Fluted Paperboard	10.2	average weight clamshell from PSPC study	2.1	10.2 - 10.3
Solid PLA	23.3	average weight of actual samples of PLA clamshells obtained and weighed by Franklin Associates	4.9	N/A

(1) For samples of 24 oz PLA cups and 24 oz PP cups made by the same producer, the PLA cup was 50% heavier than the same size PP cup. This weight ratio was applied to the weight of a 32 oz PP cup (23.3 g) to estimate the weight of a 32 oz PLA cup (23.3 x 1.5 = 35.0 g).
(2) Using resin densities of 0.90 g/cm3 for PP and 1.25 g/cm3 for PLA, a product made of PLA would weigh 1.39 times as much as a product made of the equivalent volume of PP resin. 23.3 g PP cup x 1.25/0.9 = 32.4 g PLA cup.
(3) For samples of PLA clamshells and solid (non-foam) PS clamshells made by the same producer, the PLA clamshell was 15% heaver than the same size PS clamshell. This weight ratio was applied to the weight of a solid PS plate (18 g) to estimate the weight of the same size solid PLA plate (18 g PS plate x 1.15 = 20.7 g PLA plate).

Source: Franklin Associates, A Division of ERG.

In this analysis, the end-of-life carbon footprint for each product is extended to include estimates of carbon dioxide from WTE combustion of materials, methane from decomposition of degradable landfilled material, emission credits for avoided grid electricity displaced by electricity generated from WTE energy and landfill gas combustion, and carbon sequestration in landfilled biomass-derived material that does not decompose. The primary sources of information for modeling the carbon footprint for landfilling and incineration were U.S. EPA reports containing information on generation and management of landfill methane[3,4], and a published article on methane generation from decomposition of materials in simulated landfill conditions.[5] According to the website of NatureWorks LLC, the sole commercial producer of PLA in the U.S., PLA does not biodegrade in landfills.[6]

Assumptions about the decomposition of landfilled paperboard foodservice products have a significant effect on the end-of-life global warming potential results for paperboard products. This analysis includes end-of-life results for decomposition scenarios ranging from no decomposition to maximum decomposition of bleached paperboard from landfill simulation experiments. The greenhouse gas emissions are based on anaerobic decomposition, producing an equimolar mixture of carbon dioxide and methane. Additional sensitivity analyses are shown in Chapter 3 examining the effects of alternative scenarios for reduced gas production and higher oxidation rates of methane in landfill cover.

The focus of this analysis is on the differences in environmental profiles for the products themselves. Secondary packaging is not included. The scope of this analysis does not include recycling or composting of any of the products studied. These issues were addressed in the 2006 PSPC study. Readers interested in the contribution of secondary packaging or the impacts of low levels of composting and recycling of foodservice products are encouraged to refer to the 2006 study.

FUNCTIONAL UNIT

In a life cycle study, products are compared on the basis of providing the same defined function (called the **functional unit**). The function of disposable foodservice products is to contain beverages or food for a single use. The functional unit in this analysis is 10,000 items of each foodservice product.

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3 U.S. EPA. **Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks.** Third Edition. September 2006. http://www.epa.gov/climatechange/wycd/waste/downloads/fullreport.pdf

4 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.

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

6 NatureWorks LLC website, "Fact or Fiction?" section. http://www.natureworksllc.com/product-and-applications/fact%20or%20fiction.aspx#meth. Accessed in March 2008.

In the hot cup application, corrugated cup sleeves are evaluated as an optional add-on for the poly-coated and PLA-coated paperboard cups. 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.

RESULTS

The presentation of results focuses on energy, solid waste, global warming potential, and water use for each product studied. Because there are large uncertainties about the actual decomposition of landfilled paperboard products, two sets of results are shown for paperboard products. One scenario is based on maximum decomposition of the paperboard, and the other is based on no decomposition. Tables containing additional detail on each system are provided in Chapter 2. Observations and conclusions are summarized at the end of the Executive Summary.

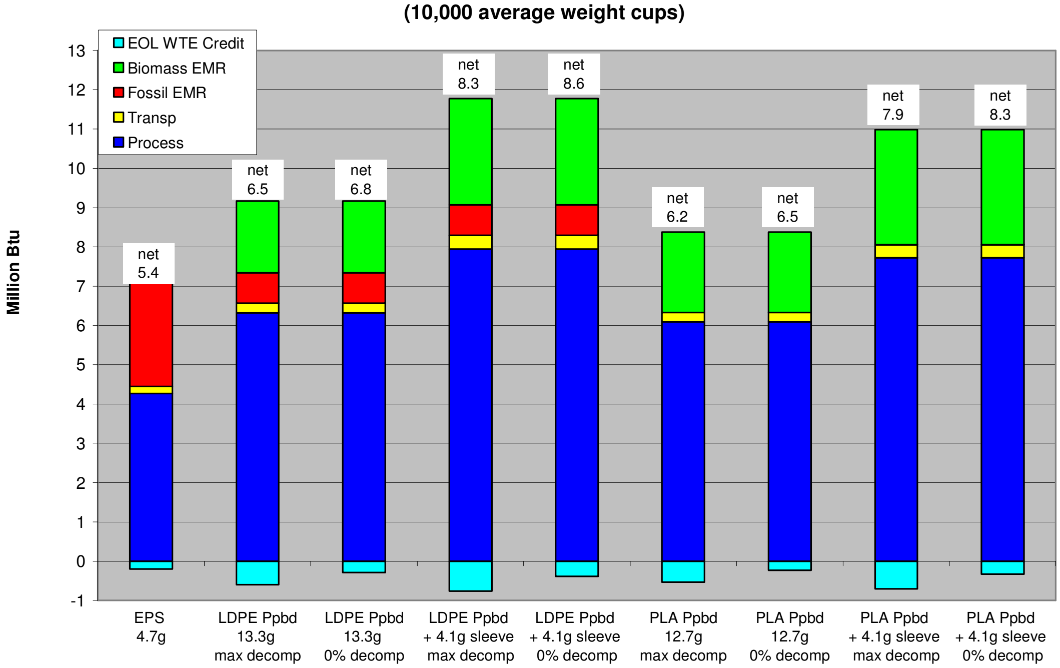
Energy Results

Total energy results for each foodservice product are shown in Figures ES-1 through ES-4, using the following categories:

- **Process energy** includes energy for all processes required to produce each foodservice item, from acquisition of raw materials through manufacture of the finished item, as well as operation of equipment used in landfilling postconsumer items.
- **Transportation energy** is the energy used to move material from location to location during its journey from raw material to finished product, and for collection and transport of postconsumer material.
- **Energy of material resource (EMR)** is not an expended energy but the energy value of resources removed from nature and used as material inputs for the product systems. For plastic resins, the EMR is associated with fossil resources (crude oil, natural gas) that are predominantly used as fuel resources. For paperboard and PLA, the EMR reflects the energy content of harvested trees and corn. These biomass materials are normally used as materials or food but can be used as a source of energy. In this study, EMR for biomass materials is shown separately from fossil EMR for plastics. As shown in Figures ES-1 through ES-4, the decision whether or not to include biomass EMR (the green segment in the figures) has a large influence on total energy results and conclusions.
- **End of life energy credit** is based on the amount of useful energy recovered from end-of-life management of the containers, based on the U.S. average municipal solid waste disposition for materials that are not recovered for recycling. The energy credit includes energy recovered from waste-to-energy combustion of 20 percent of the postconsumer products and from combustion of landfill gas recovered from decomposition of landfilled paperboard products.

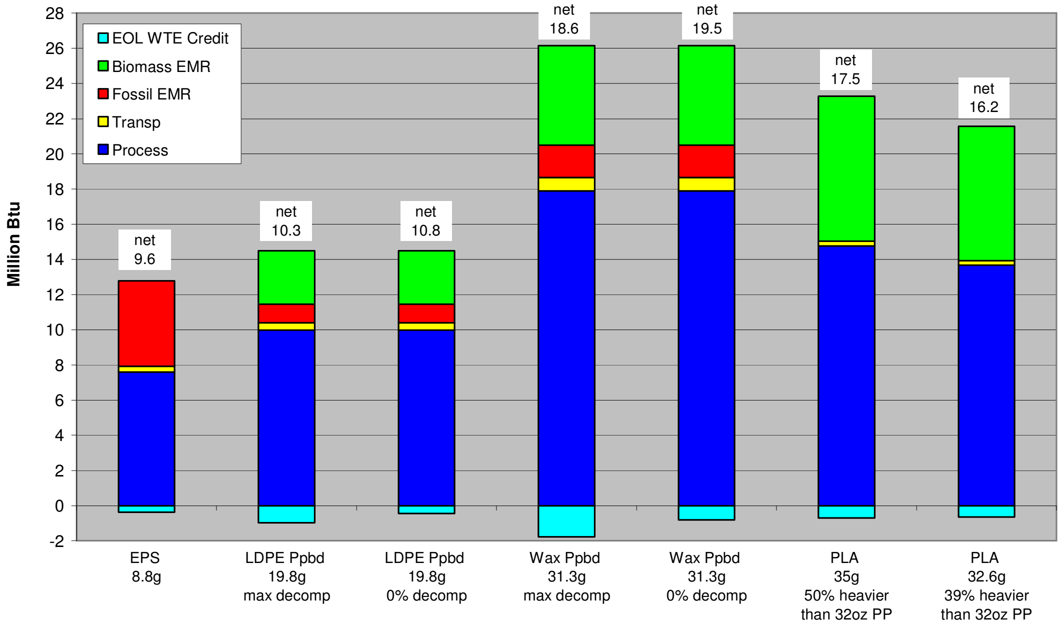
The process and transportation energy segments shown in the figures represent energy that has been completely expended (e.g., from combustion of fuels). For the energy reported as EMR, much of this energy remains embodied in postconsumer products that are sent to landfills at end of life. The *net expended* energy for each system is calculated as the energy content of the resources extracted as material feedstock for the product, plus the process and transportation energy, minus the energy content in landfilled products, minus the energy recovered at end of life from combustion of products and combustion of recovered landfill gas from decomposition of landfilled products. The net expended energy value is shown above each detailed energy bar.

Figure ES-1. Energy for 16-oz Hot Cups (10,000 average weight cups)



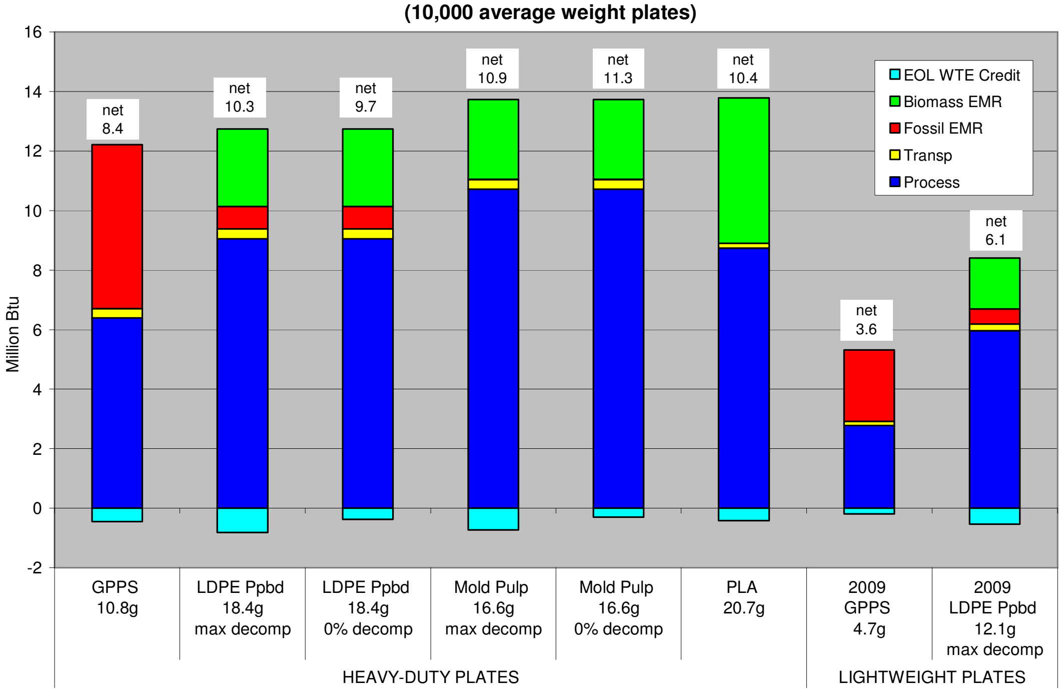
Net expended energy = total energy requirements - energy recovery - energy content of landfilled material

Figure ES-2. Energy for 32-oz Cold Cups
(10,000 average weight cups)



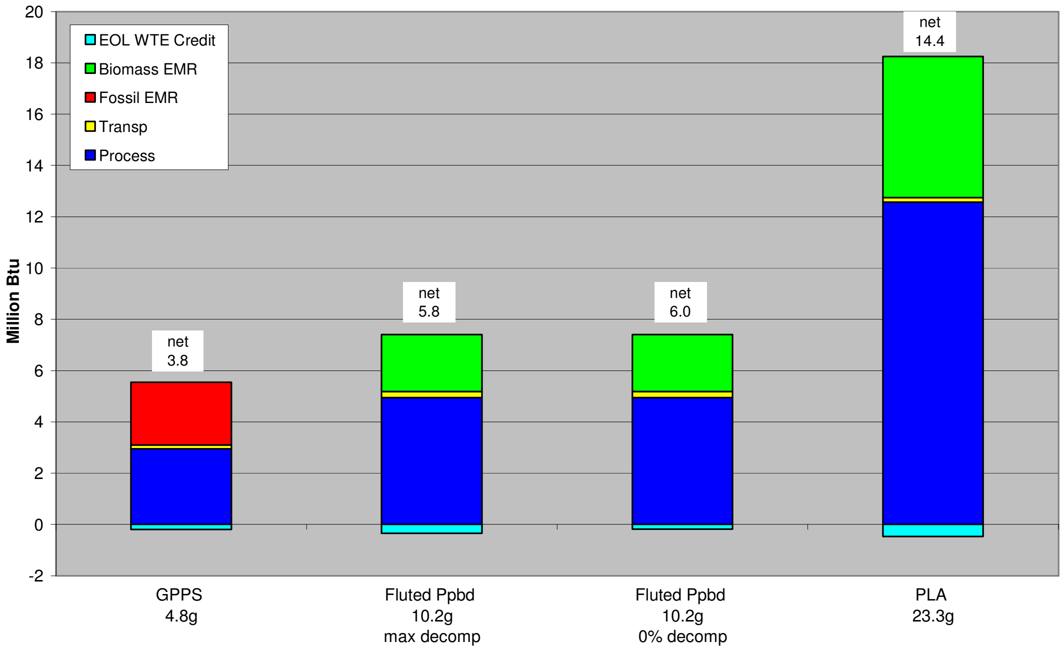
Net expended energy = total energy requirements - energy recovery - energy content of landfilled material

Figure ES-3. Energy for 9-inch Plates
(10,000 average weight plates)



Net expended energy = total energy requirements - energy recovery - energy content of landfilled material

Figure ES-4. Energy for Sandwich-size Clamshells (10,000 average weight clamshells)



Net expended energy = total energy requirements - energy recovery - energy content of landfilled material

Solid Waste Results

Solid waste results are shown in two sets of figures. Figures ES-5 through ES-8 show the total weight of solid waste separated into the following 3 categories:

- **Process wastes** are the solid wastes generated by the various processes from raw material acquisition through production of foodservice products.
- **Fuel-related wastes** are the wastes from the production and combustion of fuels used for process energy and transportation energy.
- **Postconsumer wastes** are the foodservice products that are landfilled at end of life, plus any ash resulting from waste-to-energy combustion of disposed products.

Figures ES-9 through ES-12 show the same results converted to a volume basis using landfill densities that take into account not only the density of the material as put into the landfill but also the degree to which the material compacts in the landfill. Comparing the weight-based and volume-based figures, it can be seen that different comparative conclusions can be reached about solid waste depending on whether a weight or volume basis is used.

Both solid waste figures show that the majority of solid waste, whether reported by weight or by volume, is associated with postconsumer products.

The lower the landfill density, the more space the component takes up. For example, foam plates have a lower landfill density than paperboard plates, so a pound of foam plates takes up more landfill space than a pound of paperboard plates.

Figure ES-5. Weight of Solid Waste for 16-oz Hot Cups (10,000 average weight cups)

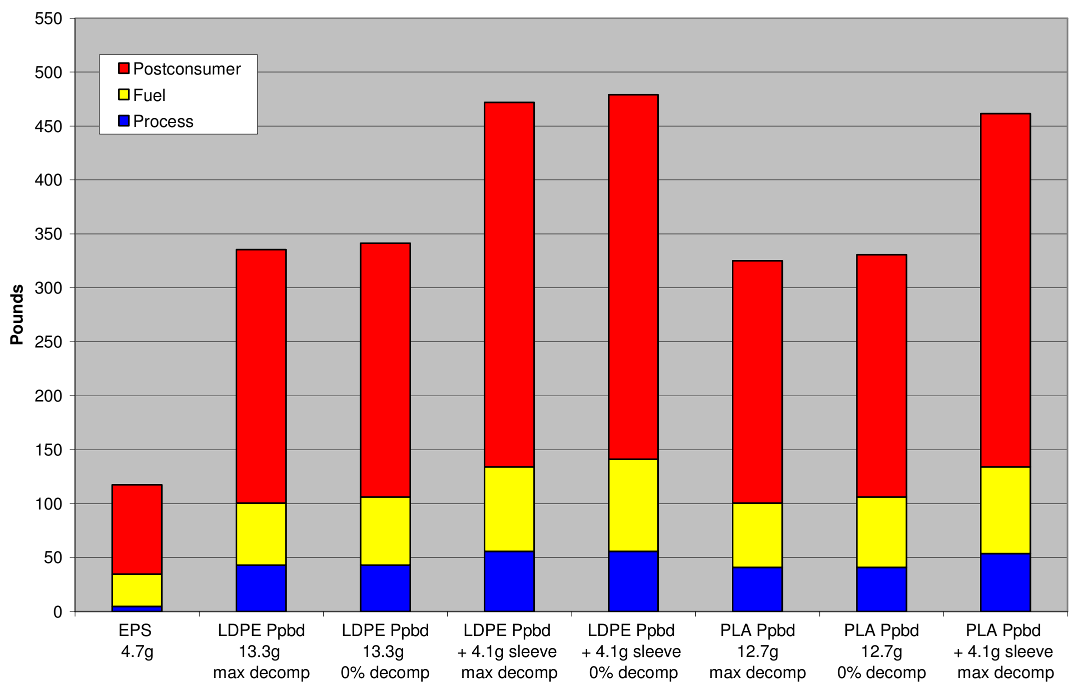


Figure ES-6. Weight of Solid Waste for 32-oz Cold Cups (10,000 average weight cups)

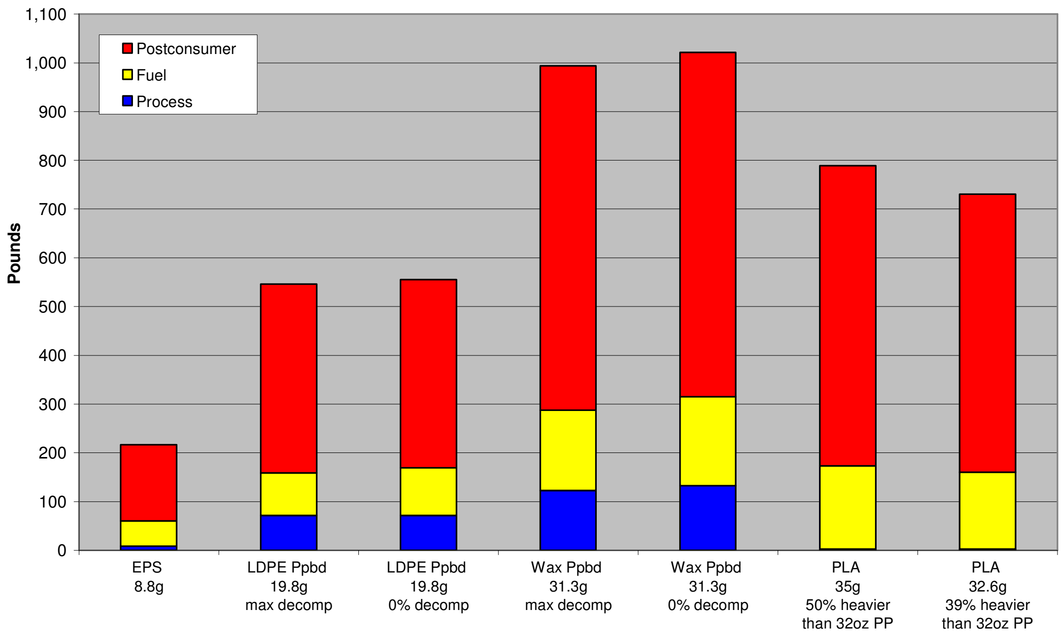


Figure ES-7. Weight of Solid Waste for 9-inch Plates (10,000 average weight plates)

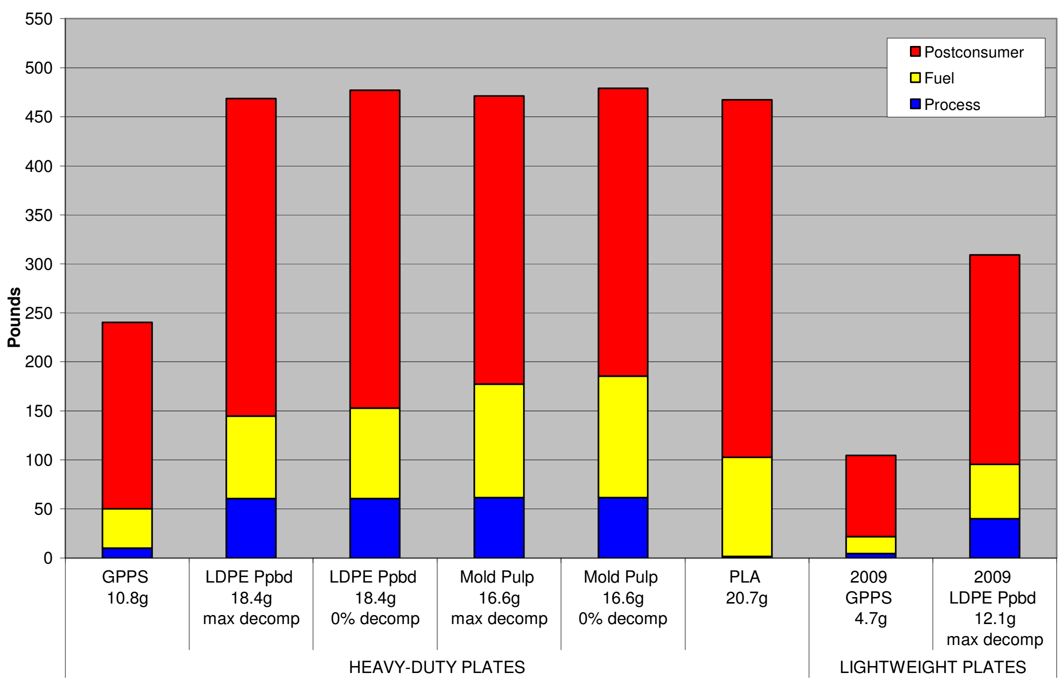


Figure ES-8. Weight of Solid Waste for Sandwich-size Clamshells (10,000 average weight clamshells)

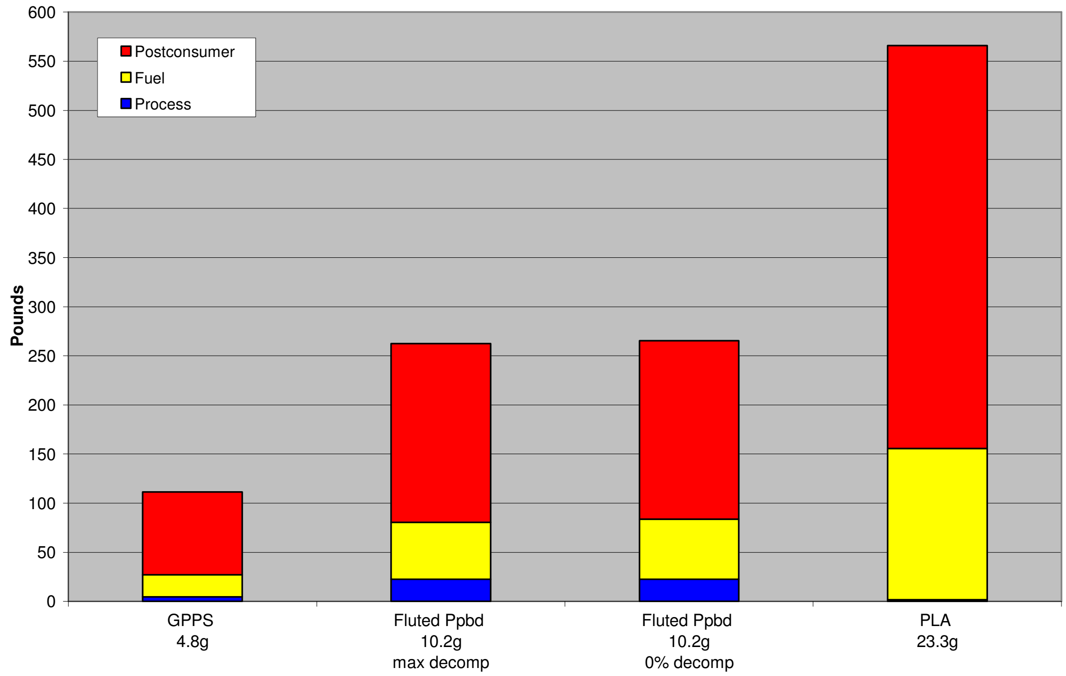


Figure ES-9. Volume of Solid Waste for 16-oz Hot Cups (10,000 average weight cups)

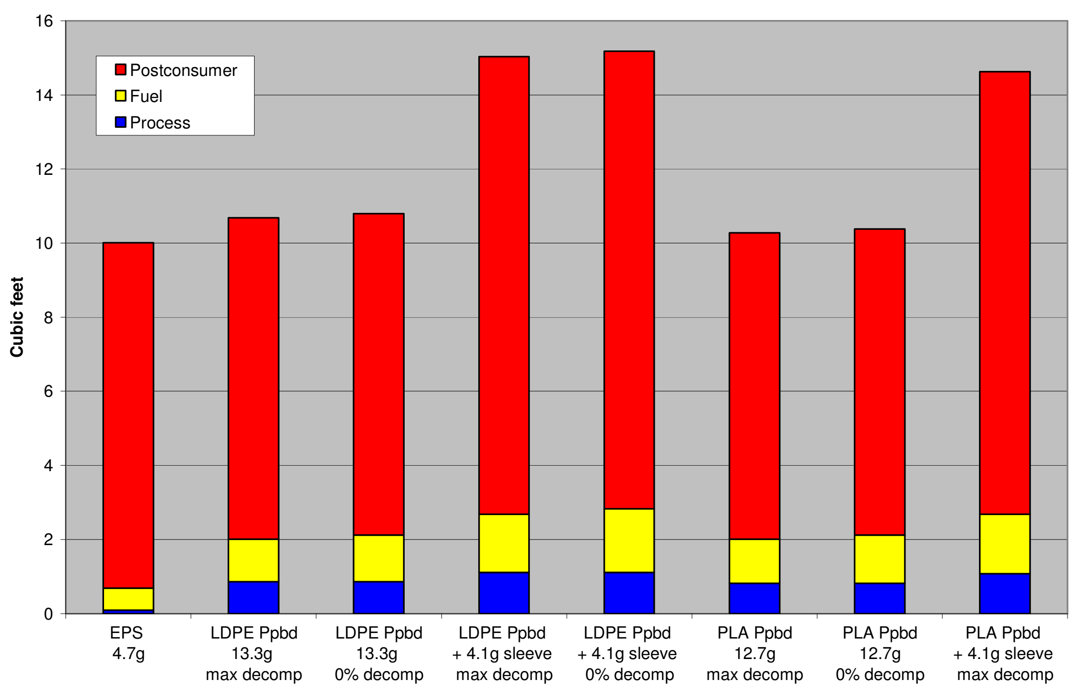


Figure ES-10. Volume of Solid Waste for 32-oz Cold Cups (10,000 average weight cups)

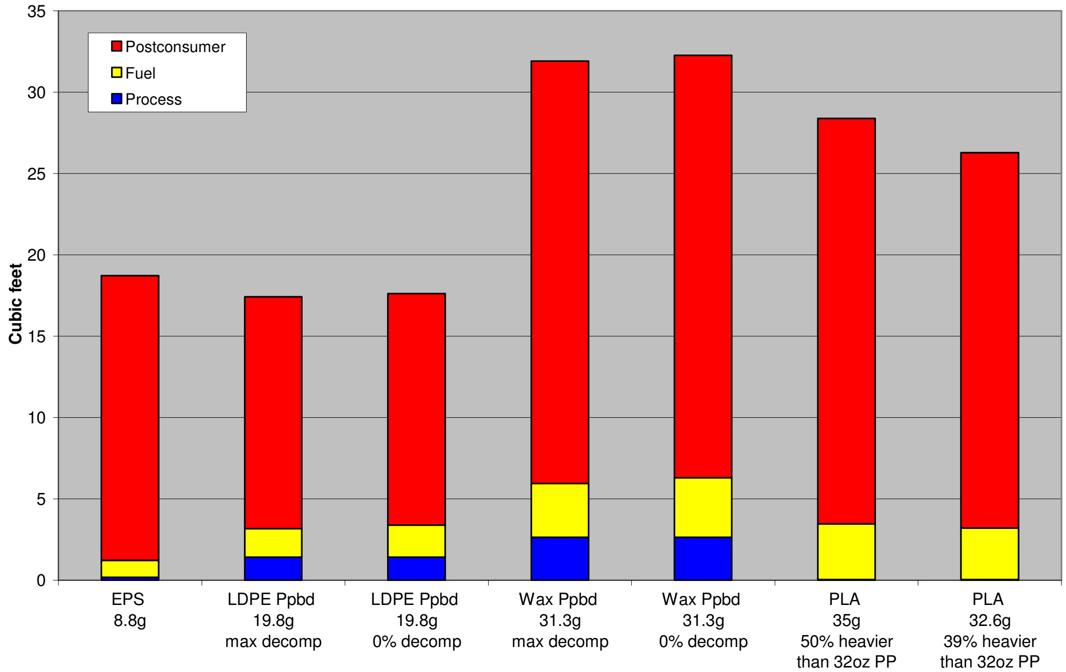


Figure ES-11. Volume of Solid Waste for 9-inch Plates (10,000 average weight plates)

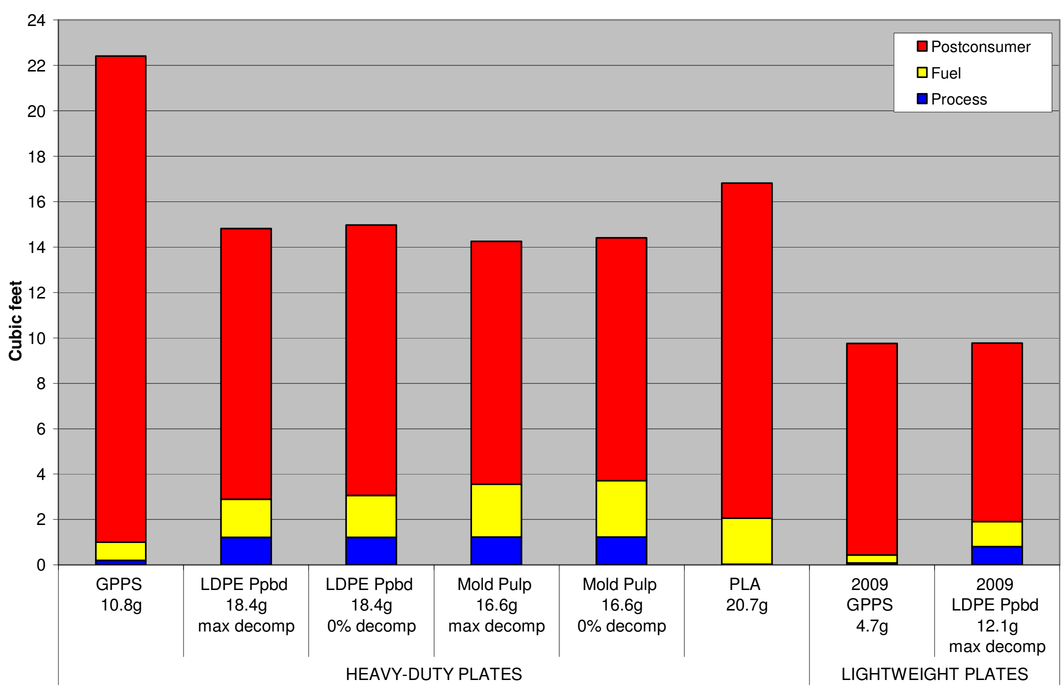
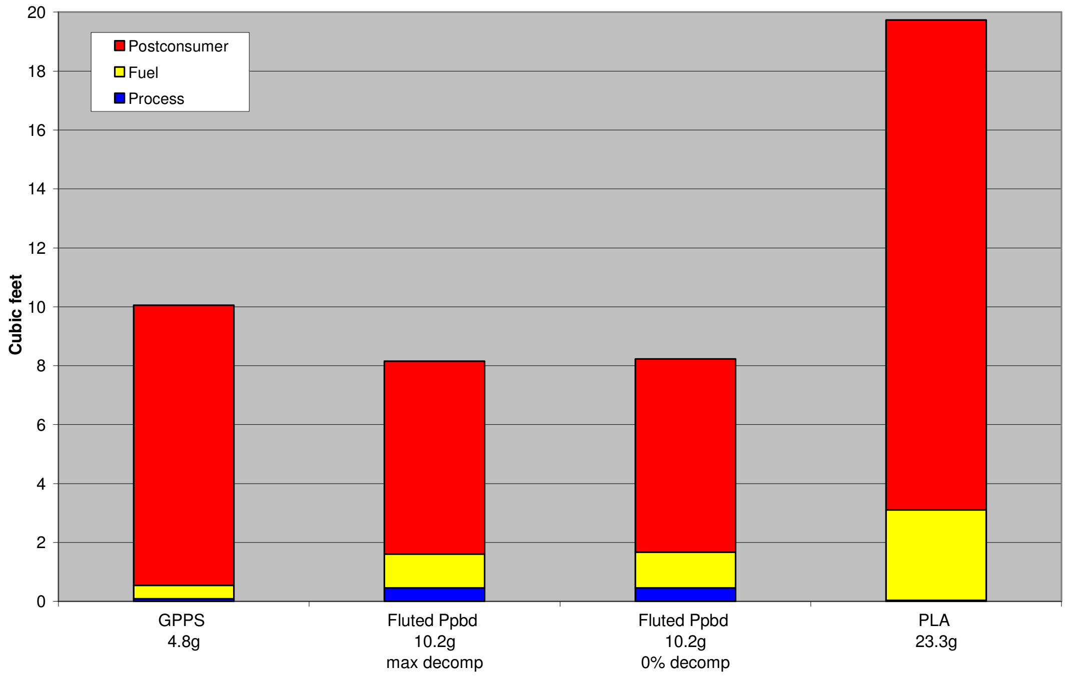


Figure ES-12. Volume of Solid Waste for Sandwich-size Clamshells (10,000 average weight clamshells)

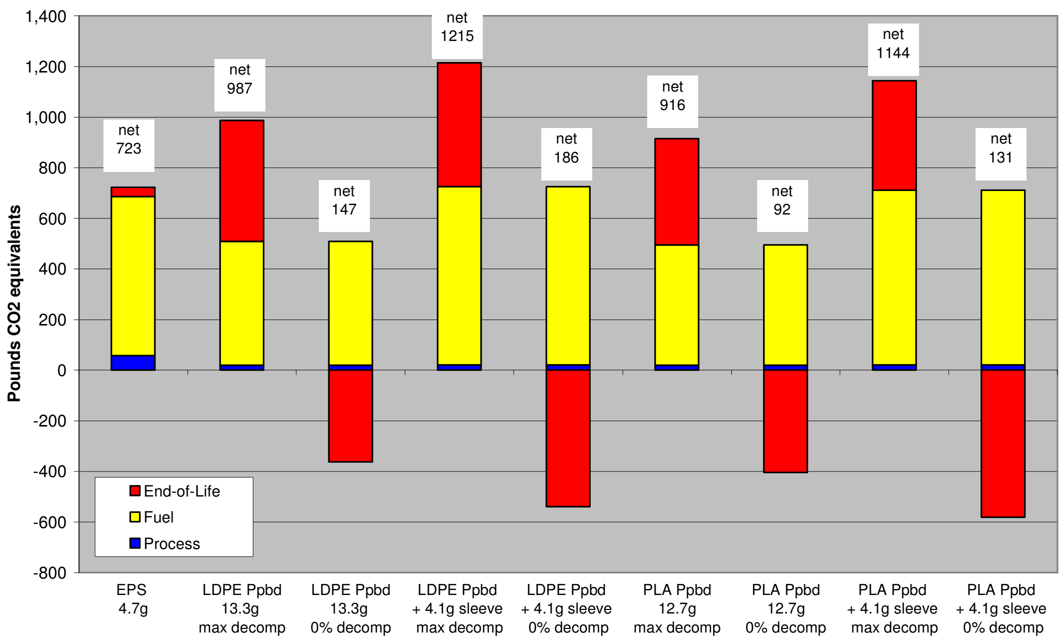


Greenhouse Gas Results

The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. Each greenhouse gas has a global warming potential (GWP) that represents the relative global warming contribution of a pound of that particular greenhouse gas compared to a pound of carbon dioxide. The weight of each greenhouse gas from each product system is multiplied by its GWP to convert it to equivalent pounds of carbon dioxide (CO_2 eq), then the CO_2 eq for each greenhouse gas are added to arrive at a total CO_2 eq for each product system. Figures ES-13 through ES-16 show the CO_2 eq contributions related to process emissions, fuel-related emissions, and end-of-life management of foodservice products. The net CO_2 eq value is shown above each detailed results bar.

All CO_2 calculations, including CO_2 eq calculations for the aggregated methane releases from decomposition of landfilled paper products, are based on 100-year GWP factors published in the IPCC Second Assessment report (SAR), published in 1996.[7] 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.[8] The IPCC SAR 100-year global warming potentials (GWP) are 21 for methane and 310 for nitrous oxide.

Figure ES-13. Greenhouse Gas Emissions for 16-oz Hot Cups
(lb CO2 eq per 10,000 average weight cups)



7 **Climate Change 1995: The Science of Climate Change.** Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. IPCC 1996. GWP factors are shown in Table 4.

8 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).

Figure ES-14. Greenhouse Gas Emissions for 32-oz Cold Cups (lb CO2 eq per 10,000 average weight cups)

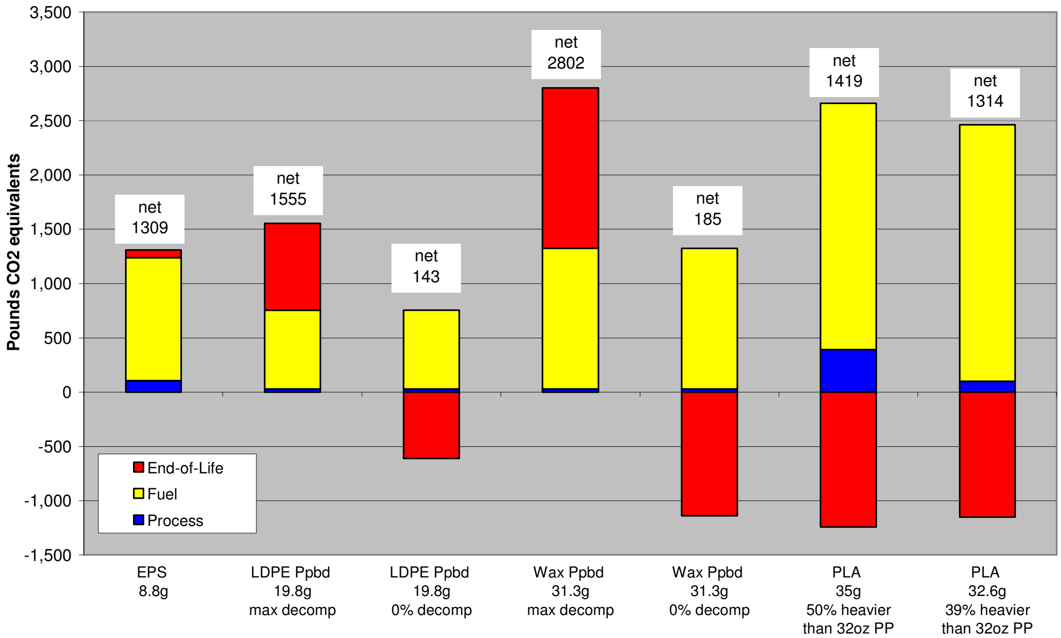


Figure ES-15. Greenhouse Gas Emissions for 9-inch Plates (lb CO2 eq per 10,000 average weight plates)

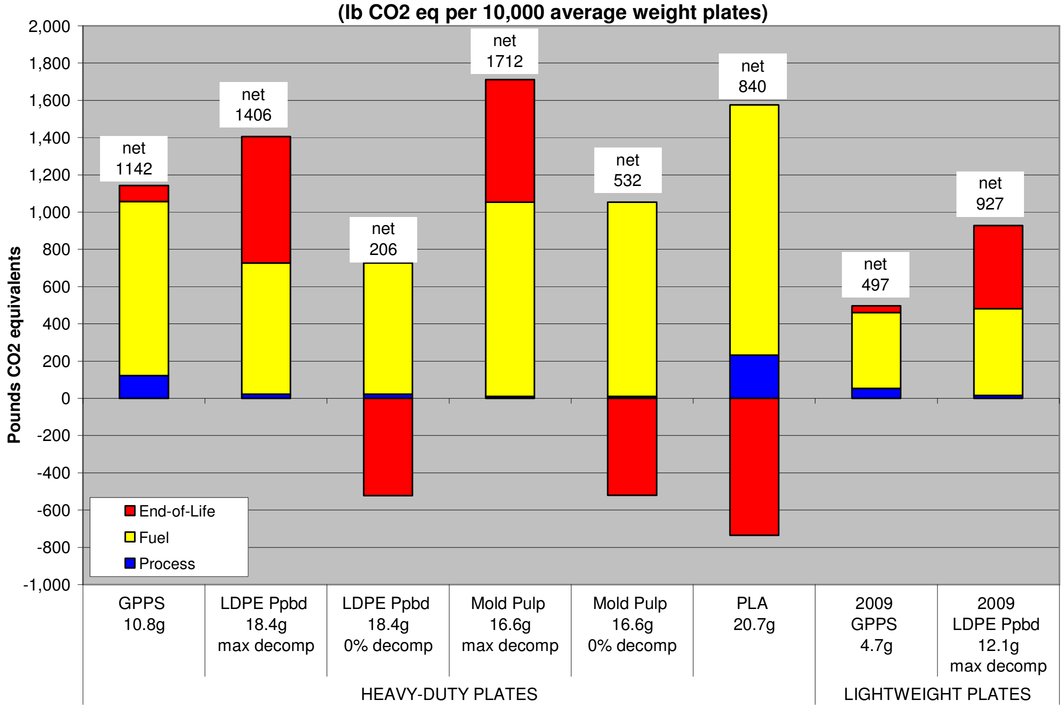
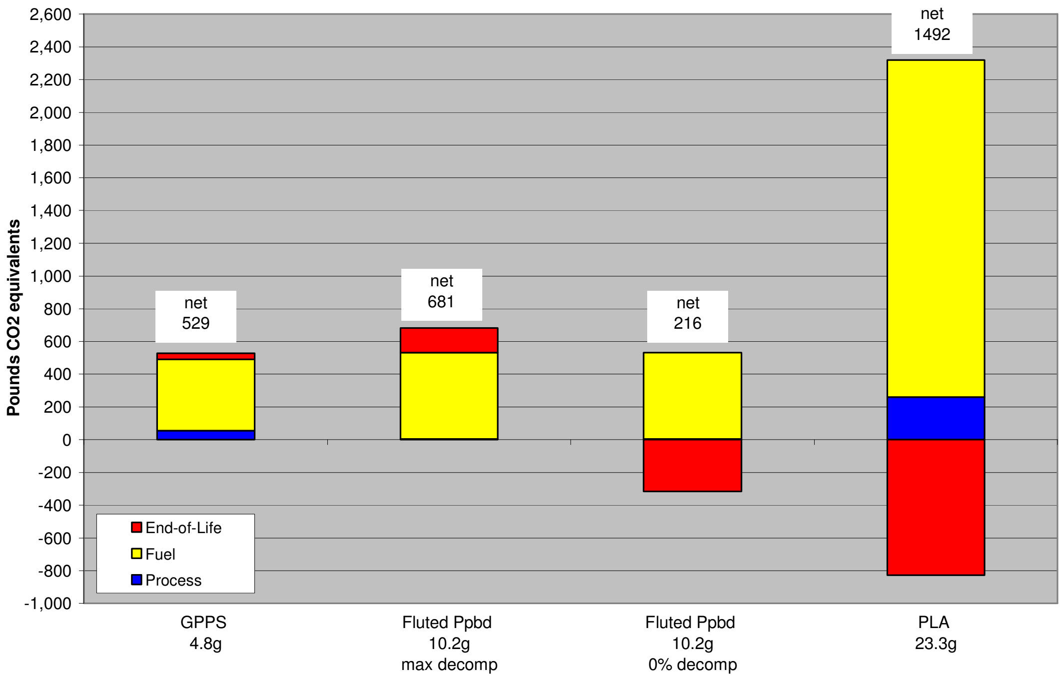


Figure ES-16. Greenhouse Gas Emissions for Sandwich-size Clamshells
(lb CO2 eq per 10,000 average weight clamshells)



The "Net End of Life" segment in Figures ES-13 through ES-16 includes estimates for the greenhouse gas effects of end-of-life management of foodservice products, including energy credits for useful energy that is recovered from waste-to-energy combustion of postconsumer items and from waste-to-energy combustion of recovered landfill gas. The methodology and data sources for these calculations are described in detail in the End-of-Life Management section of Chapter 1. The end-of-life GHG results should be considered to have a higher uncertainty than the process and fuel-related GHG results. For paperboard items, the end-of-life GHG results are strongly dependent on assumptions about decomposition in landfills and the fate of methane produced from decomposition. However, some general observations can be made.

Neither PS nor PLA decomposes to produce methane in landfills.[9,10] For the biomass-derived PLA content of the foodservice products, there is a net end-of-life CO_2 eq credit for carbon sequestered in landfilled PLA products and for grid electricity emissions that are displaced by electricity from WTE combustion of PLA products. Polystyrene foam products show a small net increase in CO_2 eq because the fossil CO_2 emissions from WTE combustion of fossil resins are greater than the emission credits for grid electricity displaced by the recovered energy. Although PS has a high carbon content and does not decompose to produce methane in landfills, no carbon sequestration credit is assigned to fossil-derived plastics. This is consistent with the U.S. EPA greenhouse gas accounting methodology, which treats landfilling of plastic as a transfer from one carbon stock (the oil field) to another carbon stock (the landfill) with no net change in the overall amount of carbon stored.[11]

When paperboard foodservice products decompose anaerobically, methane is generated. The landfill methane emissions estimated in this analysis represent the *cumulative* releases of methane from decomposition, which will occur over a period of many years. In addition to decomposition emissions, fossil CO_2 is released from the resin coatings when coated paperboard products are burned in WTE combustion facilities. There are credits for carbon sequestration in the undecomposed paperboard and credits for displacement of grid electricity when energy is recovered from WTE combustion of landfill gas and from WTE combustion of disposed postconsumer paperboard products.

When paperboard foodservice products are modeled at maximum experimental decomposition levels, the overall effect of end-of-life management activities for these products is a net increase in CO_2 eq, because the CO_2 eq for the cumulative fugitive methane emissions is much greater than the CO_2 eq credits for WTE combustion and sequestration in landfilled material that does not decompose.

When paperboard products are modeled at 0 percent decomposition, however, the net end-of-life results are very different. At 0 percent decomposition, no methane is produced and all the carbon content of the paperboard is sequestered in the landfilled products, so that there is a large net CO_2 eq credit for paperboard products.

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

10 NatureWorks LLC website, "Fact or Fiction?" section.

11 U.S. EPA. **Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks.** Third Edition. September 2006. Page 6.

Water Use

Water use data were not available for many of the unit processes associated with the production of the foodservice products in this analysis, resulting in data gaps when attempting to construct models for product systems on a unit process basis. Therefore, it was necessary to use aggregated cradle-to-material data sets for most of the materials modeled. Furthermore, data sources did not distinguish between consumptive use of cooling water and recirculating use of cooling water. Since it was not possible to differentiate between consumptive and non-consumptive use of water, the water results shown throughout this report are referred to as water *use* rather than water *consumption*. Because of the use of aggregated cradle-to-material water use data, and the inability to clearly differentiate between consumptive and non-consumptive uses of water, the water use results presented here should be considered to have a high degree of uncertainty. Total water use for each foodservice product system shown in Figures ES-17 through ES-20 includes process water use and cooling water use, including cooling water associated with electricity generation.

Polystyrene resin products requires very little process water compared to paperboard and PLA products. Process water use for paperboard and PLA includes water used in pulping operations, corn irrigation, corn wet mills, and other processes used to convert corn to PLA. Cooling water use per pound is higher for production of PS foam products and PLA products compared to paperboard products, since molding and thermoforming of resins requires more electricity compared to the processes used to convert paperboard into cups, plates, and clamshells.

Figure ES-17. Gallons of Water Used for 16-oz Hot Cups
(10,000 average weight cups)

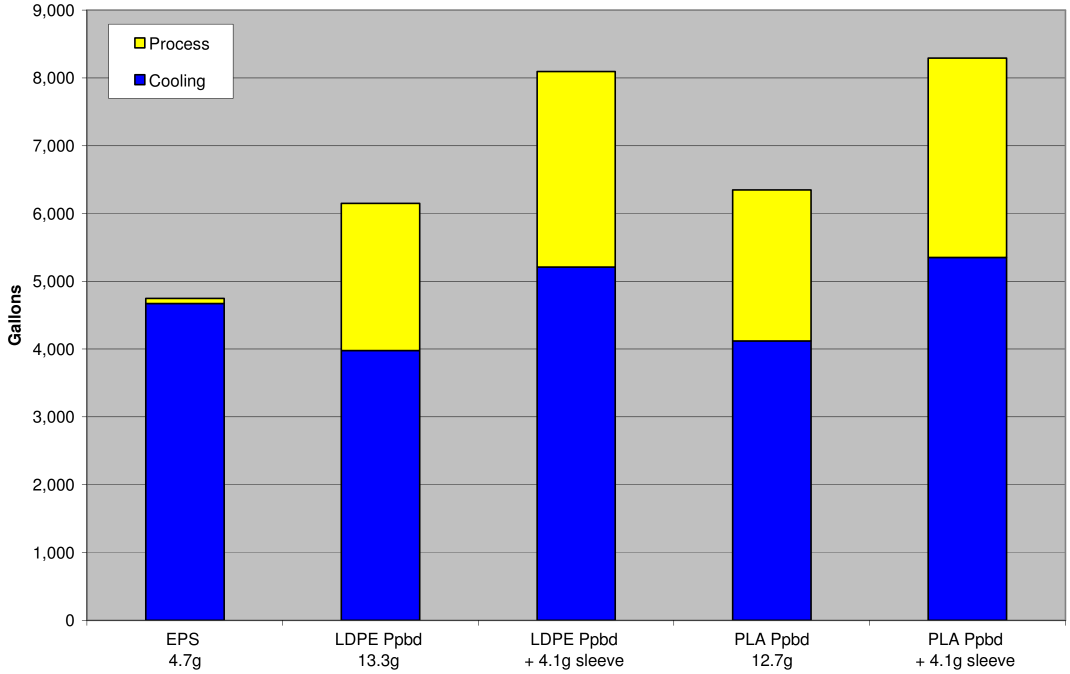


Figure ES-18. Gallons of Water Used for 32-oz Cold Cups
(10,000 average weight cups)

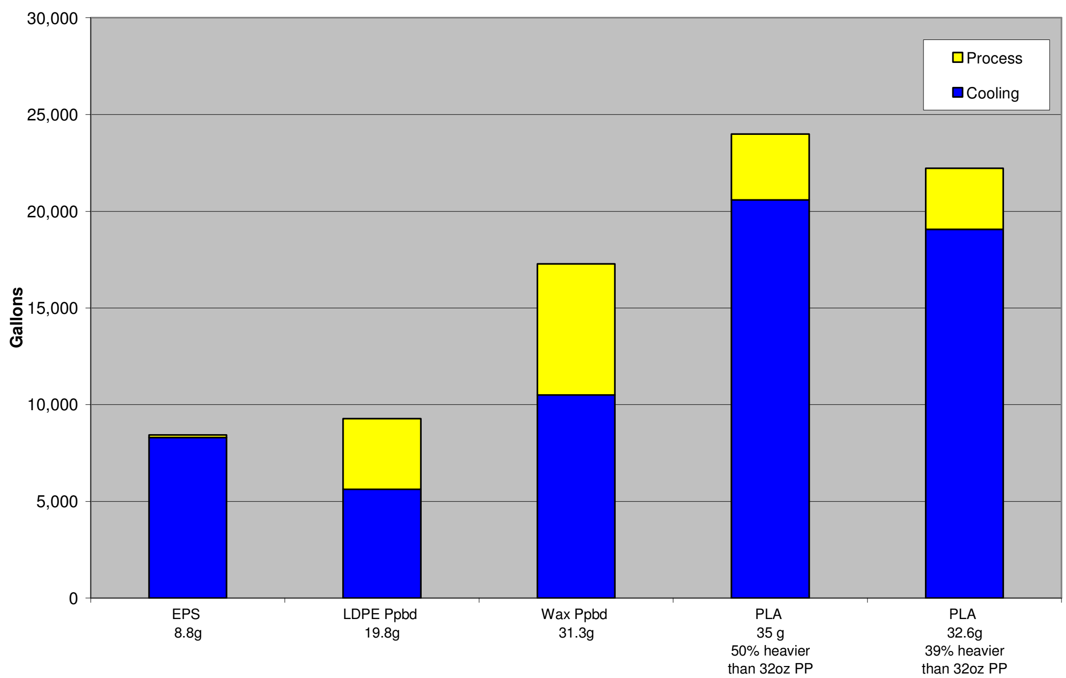


Figure ES-19 Gallons of Water Used for 9-inch Plates (10,000 average weight plates)

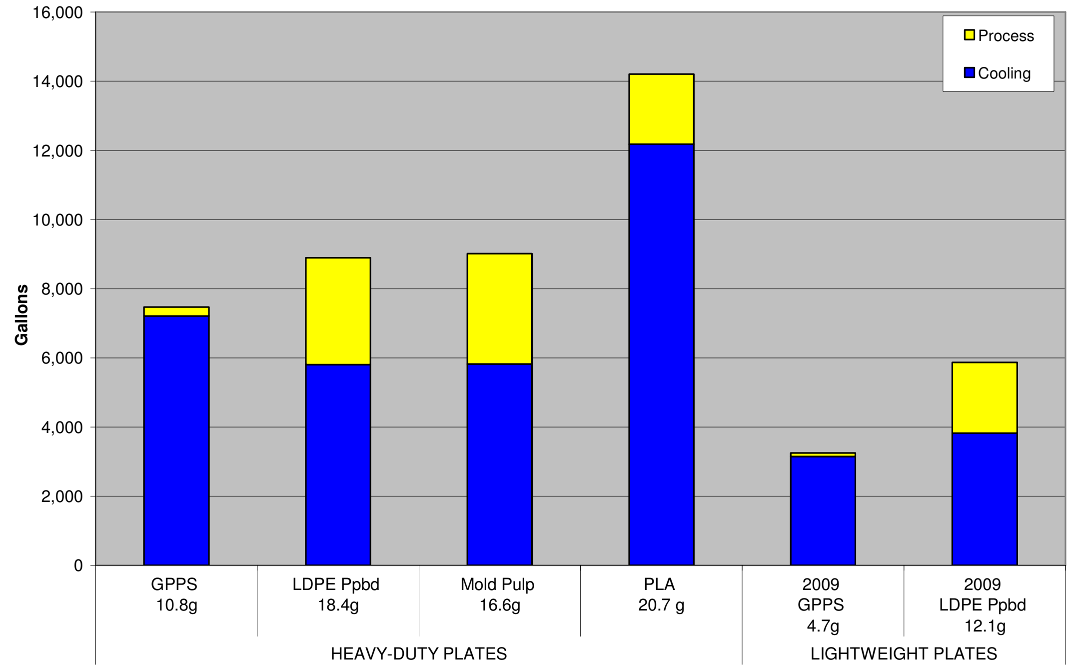
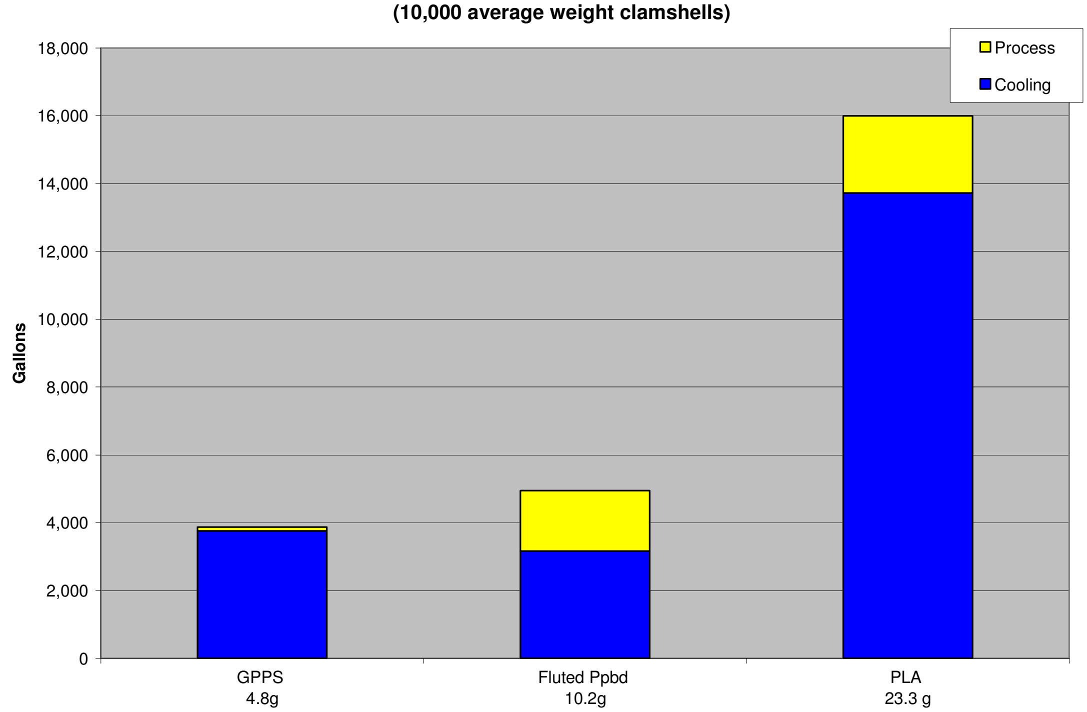


Figure ES-20. Gallons of Water Used for Sandwich-size Clamshells (10,000 average weight clamshells)



KEY OBSERVATIONS AND CONCLUSIONS

The observations and conclusions regarding energy, solid waste, water use and greenhouse gases are all sensitive to the assumptions and choices made in this study about

- Product weight
- Inclusion of bio-based EMR
- Solid waste reporting basis (by weight or by volume)
- Decomposition of products in landfills and management of methane produced from decomposition
- Exclusion of indirect land use change
- Corn irrigation practices
- Choice of allocation method.

The following observations and conclusions are based on the assumptions made in this study and apply to the specific product weights analyzed in this report. The results, observations, and conclusions should not be considered representative of the full range of product weights that may be available in the marketplace.

- **Influence of Product Weight on LCI Results:** The majority of the environmental burdens for producing each type of foodservice item is from the production of the materials used. Material production burdens for a product are calculated as the product of the burdens per pound of material multiplied by the pounds of material used in the product system. Many grades and weights of disposable foodservice products are available in the marketplace. As shown in Table ES-1, all paperboard and PLA products analyzed in this study are heavier than the corresponding average weight PS foam product. Comparisons of products with different weight ratios may yield different conclusions. This can be seen in the plate tables, where there are large differences in the results for average weight high-grade plates and results for lighter weight plates from a 2009 LCI study.

- **Energy:** For the product weights modeled, the total energy requirements for average PS foam products across the different product categories are generally lower than total energy requirements for the equivalent number of (heavier) PLA or paperboard products analyzed. Total energy requirements for LDPE-coated cold cups, LDPE-coated plates, and molded pulp plates are not significantly different from energy requirements for the corresponding PS products.

- **Net Energy Consumption:** A significant portion of the total energy requirements for each product is energy of material resource. Some of the EMR remains embodied in the postconsumer products that are sent to landfills at end of life. Some energy is also recovered from postconsumer materials that are managed by WTE combustion, as well as from WTE combustion of landfill gas produced from paperboard decomposition.

- **Solid Waste:** Comparative conclusions about solid waste differ depending whether the results are expressed in terms of weight or volume of waste. Postconsumer products account for the largest share of solid waste for each system. The plastic foam systems produce less *weight* of solid waste compared to heavier paperboard and PLA products. However, because of the low density of foam products, the differences in solid waste *volume* of postconsumer foam products and corresponding paperboard or solid resin products become relatively small for most product categories. For plates, heavy-duty PS foam plates produce a greater volume of solid waste than other types of heavy-duty plates; however, for the 2009 equivalent strength plate comparison, the PS foam and paperboard plates have very similar solid waste volumes.

- **Greenhouse Gas Results:** The majority of GHG emissions for most systems studied are associated with combustion of fossil fuels for process and transportation energy. For the PLA system, there are also significant process GHG emissions associated with nitrous oxide emissions from fertilizer use for corn. The **end-of-life** greenhouse gas results presented here should be considered more uncertain than other emissions data. End-of-life management results in a small net increase in GHG for PS foam products and a net GHG credit for PLA products. End-of-life results for paperboard products vary considerably depending on assumptions about decomposition. At maximum experimental decomposition levels, the overall effect of the estimated GHG additions and credits from end-of-life management is a large net increase in GHG for paperboard products. At lower decomposition rates, the net end-of-life GHG for paperboard products is much smaller, since less methane is released and more carbon is sequestered in undecomposed material. If the paperboard does not decompose, no methane is produced and all the biomass carbon in the paperboard product is sequestered, resulting in a large carbon sequestration credit.

- **Limitations of Water Use Data:** Because of a lack of unit process-level data on water use, the water use results in this analysis are largely based on aggregated cradle-to-material data sets and estimates based on literature. In addition, data sources did not distinguish between consumptive use of cooling water and recirculating use of cooling water. Every effort was made to provide corresponding coverage of water use for each product system; however, without access to the supporting unit process data, and lacking distinction between consumptive and non-consumptive uses of water, it was not possible to ensure that different cradle-to-material data sets were derived using consistent methodologies. Therefore, the comparative water use results in this report have a high degree of uncertainty.

- **Water Use Results:** Across the different product categories, water use for the average weight paperboard product in each category is 20 to 30 percent higher than for the corresponding average weight PS foam product, and water use for the solid PLA product is 2 to 4 times as high as for the corresponding PS foam product. The differences in the weights of the solid PLA and PS foam products are a significant driver for the comparative water use results.

CHAPTER 1

LIFE CYCLE METHODOLOGY

OVERVIEW

The life cycle inventory (LCI) presented in this study quantifies the total energy requirements, energy sources, atmospheric pollutants, waterborne pollutants, and solid waste resulting from the production and end-of-life management of several types of disposable foodservice products.

This analysis does not include impact assessment. It does not attempt to determine the fate of emissions, or the relative risk to humans or to the environment due to emissions from the systems. (An exception is made in the case of global warming potential impacts, which are calculated based on internationally accepted factors for various greenhouse gases' global warming potentials relative to carbon dioxide.) No judgments are made as to the merit of obtaining natural resources from various sources, for example, whether it is preferable to produce foodservice products from fuel resources (petroleum-derived plastics) or renewable resources (PLA derived from corn, or paperboard produced from trees).

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.

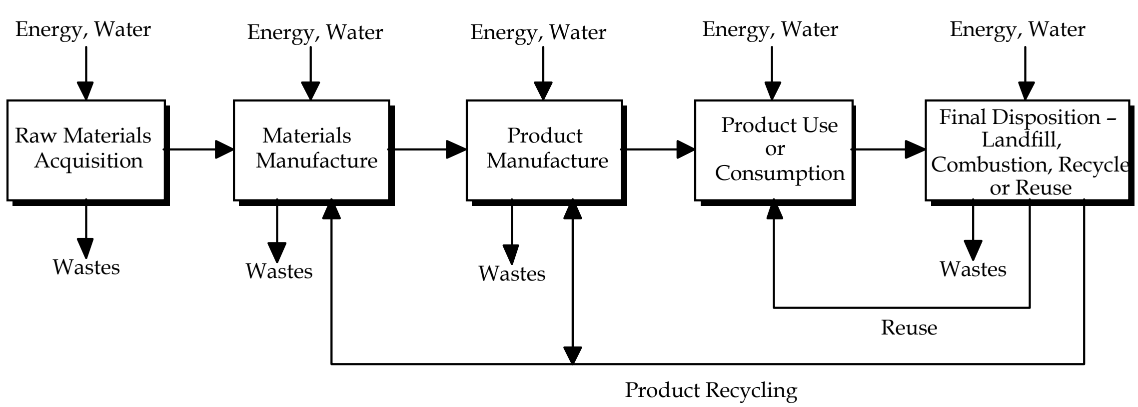


Figure 1-1. General materials flow for "cradle-to-grave" analysis of a product system.

LIFE CYCLE INVENTORY METHODOLOGY

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

Franklin Associates developed a methodology for performing resource and environmental profile analyses (REPA), commonly called life cycle inventories. This methodology has been documented for the United States Environmental Protection Agency and is incorporated in the EPA report **Product Life-Cycle Assessment Inventory Guidelines and Principles**. The data presented in this report were developed using this methodology, which has been in use for over 30 years.

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.

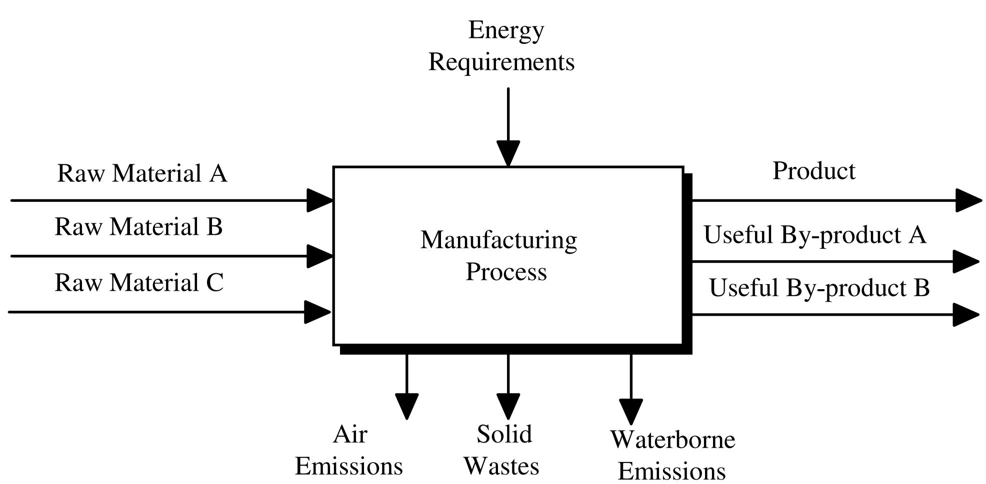


Figure 1-2. "Black box" concept for developing LCI data.

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 also assigns a fuel-energy equivalent to raw materials that are used as material feedstocks for the product systems analyzed. The energy value of the raw material is called **energy of material resource** (EMR) or inherent energy. In this study, the EMR of material feedstocks derived from fossil fuel resources (e.g., crude oil and natural gas used to produce plastic resins) is tracked separately from EMR of renewable biomass feedstocks that are not major fuel sources in North America.

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

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

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

Environmental Emissions

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

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

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

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

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

LCI PRACTITIONER METHODOLOGY VARIATION

There is general consensus among life cycle practitioners on the fundamental methodology for performing LCIs.[12] 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.

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

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"[13] or "partitioning"[14].

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

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.

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13 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.

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

In the sequence of processes used to produce resins that are used in the polystyrene products and resin coatings for paperboard cups and plates, 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.)

Scrap from product fabrication is treated as a co-product if it is recycled, and treated as a waste if it is disposed. In other words, the foodservice product system carries no burdens for material inputs that end up as fabrication scrap that is recycled into some other product. If the fabrication scrap is disposed, however, and does not end up in any other use, then the burdens for producing and disposing of the scrap are assigned to the foodservice product system. At least one manufacturer uses recycled industrial scrap as the material feedstock for molded pulp plate production; however, data from this producer were not available for this analysis. Therefore, in this analysis molded pulp plates are modeled based on production from bleached kraft market pulp.

PLA production in this study is modeled based on a cradle-to-resin dataset for NatureWorks Ingeo™ polymer. The dataset, published in the U.S. LCI Database in March 2010, covers all processes from corn growing through production of PLA resin ready to be shipped. Based on communication with the LCA practitioner who prepared the analysis, all corn growing impacts are assigned to the corn, and none to the corn stover (stalks and leaves) that are typically left in the field. The harvested corn is then processed at a corn wet mill, which produces coproducts of corn gluten feed, corn gluten meal, heavy steep water, and corn germ. As described in an LCA study using NatureWorks data[15], mass-based coproduct allocation is used to divide the corn wet mill burdens among the outputs. Because the PLA data were published as a rolled-up cradle-to-resin data set, it was not possible to further evaluate process flows for individual subprocesses or evaluate alternative allocation scenarios.

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.

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

The energy content of resources that are removed from nature for use as material feedstocks for product systems is called the **energy of material resource** (EMR) and is included in the inventory. Traditionally, Franklin has tracked EMR only for resources that are predominantly used as fuels. In the industrially developed countries included in this analysis, these materials are petroleum, natural gas, and coal. Using fossil fuels as material feedstocks removes fuel resources from the energy pool, reducing the amount of these resources available for energy use.

Total Resources

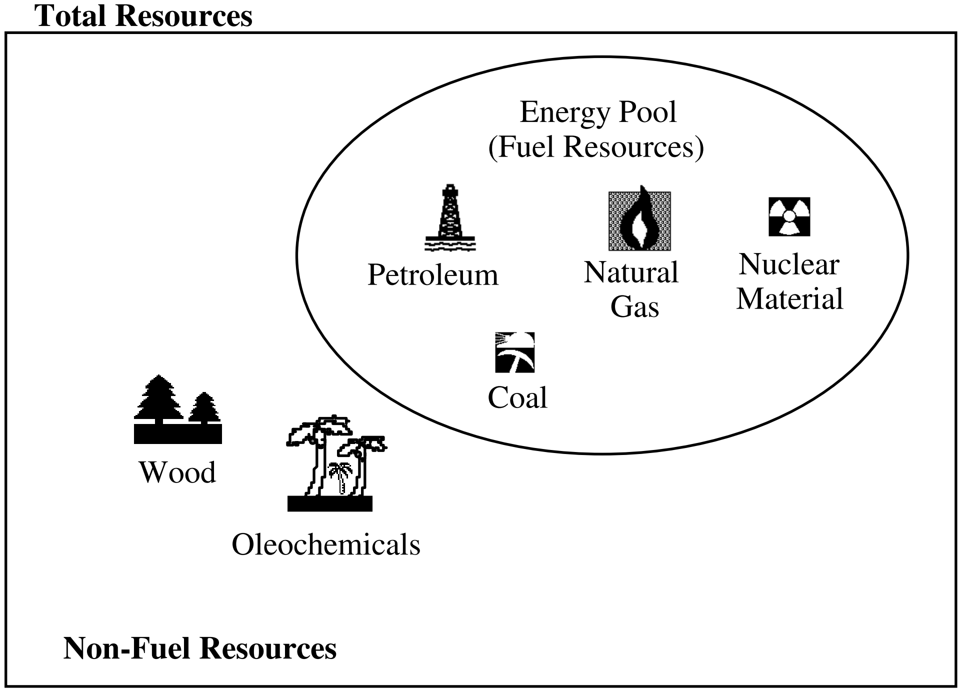

Figure 1-3. Illustration of the Energy Pool Concept.

Although EMR was originally used to track depletion of fossil fuel resources, EMR accounting can be expanded to include other material feedstocks, including renewable biomass resources such as wood and corn. Some wood is used as an energy resource, but the primary uses of wood are for making products such as paper and lumber. Corn can be used to produce bioethanol, and soy and palm oils can be used to produce biodiesel, but the primary consumption of these crops is as food or as raw materials for products such as soaps, surfactants, cosmetics, etc. Since use of these biomass feedstocks is not considered a depletion of finite fuel reserves, the energy content of biomass feedstocks used as material inputs to the foodservice products is tracked separately from fossil EMR in this analysis.

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. Biomass EMR for PLA products is based on the energy content of the harvested corn grain used for PLA production, while the biomass EMR for paperboard products is based on the energy content of the harvested wood, adjusted to subtract out the amount of process energy that is derived from the wood at the paperboard mill (e.g., via combustion of wood wastes or combustion of black liquor from the pulping process).

When the feedstock is converted to a product, the EMR becomes energy content of the product. The energy content of the product is always somewhat less than the feedstock EMR because of the energy losses associated with the steps required to convert the raw feedstocks into a finished product. The energy tables in this LCI track the energy content of landfilled products as well as the energy recovered from waste-to-energy combustion of products at end of life.

Postconsumer Recycling Methodology

When material is used in one system and subsequently recovered, reprocessed, and used in another application, there are different methods that can be used to allocate environmental burdens among different useful lives of the material. 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. In this analysis, no recycling is considered for any of the foodservice products, so no postconsumer recycling allocations are necessary.

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, composition and fabrication of plastic and paperboard products was largely based on data from the peer-reviewed PSPC life cycle inventory study, updated with fabrication data for some products provided by a private company in 2008.

Confidentiality. Franklin Associates takes care to protect data that is considered confidential by individual data providers. In order to protect product fabrication data sets provided by individual companies, the data shown in this report for each product are aggregated to include all steps from raw material acquisition through product fabrication.

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. As stated in the **Study Goal** section, the intended purpose of the study was to update and expand the environmental profiles of several types of disposable foodservice products, including polystyrene, paperboard, and PLA products. The life cycle results were developed using the most up-to-date data available.

Other than updated plate fabrication data sets from a 2009 study for a private company (used here with the permission of Pactiv) and PLA molding data from the 2006 OVAM report, data sets for all other unit processes in this study were taken from the U.S. LCI Database, the peer-reviewed PSPC study, or Franklin Associates' United States industry average database. The Franklin 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.

PLA production in this study is modeled based on a cradle-to-resin data set for NatureWorks Ingeo PLA polymer published in the U.S. LCI Database in March 2010. The dataset is specific to the supply chain and processes for Ingeo production at the NatureWorks facility in Blair, Nebraska. Since this PLA production facility accounts for all current U.S. PLA production, the PLA products in this study are modeled using the Ingeo data set. However, because the PLA data set is published as a rolled-up cradle-to-resin data set, it is not possible to further analyze the flows for individual subprocesses or evaluate alternative allocation scenarios.

Fuel Data

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

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

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

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

In 2003, Franklin Associates updated 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.

The data quality goal for this study was to use data that most accurately represents the production of current disposable foodservice products. The quality of individual data sets vary in terms of age, representativeness, measured values or estimates, etc.; however, all materials and process data sets used in this study were thoroughly reviewed for accuracy and currency and updated to the best of our capabilities for this analysis.

Data Accuracy

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

A key question is whether the LCI profiles are accurate and study conclusions are correct. The accuracy of an environmental profile depends on the accuracy of the numbers that are combined to arrive at that conclusion. Because of the many processes required to produce each foodservice product, 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. Taking into consideration budget considerations and limited industry participation, the data used in this report are believed to be the best that can be currently obtained.

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. It is assumed that with careful scrutiny of the data, any errors will be random.

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 particular 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. As noted earlier in the **Data Sources** section of this chapter, the data on corn growing should be considered to have more variability than data for other industrial processes modeled. In addition, the following section on **End of Life Management** discusses the uncertainty of the estimates of global warming potential resulting from landfilling and WTE combustion of postconsumer foodservice products.

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).

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 is managed 80 percent by weight to landfill (LF) and 20 percent by weight to waste-to-energy (WTE) incineration.[16] Thus, the calculations of the greenhouse gas impacts for discarded foodservice products are based on a scenario in which 80 percent of the postconsumer products 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 greenhouse gas (GHG) effects. There are GHG contributions from WTE combustion of postconsumer foodservice products and from fugitive emissions of landfill methane from decomposition of paperboard products. There are also GHG credits for grid electricity displaced by the generation of electricity from WTE combustion of postconsumer products and from WTE combustion of methane recovered from decomposition of landfilled paperboard products. Some carbon is also sequestered in the biomass-derived products that do not decompose. The U.S. EPA greenhouse gas accounting methodology does not assign a carbon sequestration credit to landfilling of fossil-derived materials because this is considered a transfer between carbon stocks (from oil deposit to landfill) with no net change in the overall amount of carbon stored.[17]

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16 U.S. EPA. Municipal Solid Waste Facts and Figures 2008. Accessible at http://www.epa.gov/msw/msw99.htm.

17 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.

In this study, decomposition of landfilled paperboard foodservice items is modeled based on the maximum decomposition of bleached paper in landfill simulation experiments conducted by Dr. Morton Barlaz, et al. [18] The landfill simulation experiments analyzed decomposition of office paper, clay-coated magazine paper, newspaper, and corrugated in reactors with optimized conditions for decomposition. 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 paperboard products. It is likely that the coatings on paperboard foodservice products will delay or significantly inhibit decomposition of the paper. 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 products. Alternative results for modeling lesser degrees of decomposition (50 percent of maximum decomposition, and 0 percent decomposition) are also shown in the tables and figures.

Although the Barlaz experiments included coated magazine paper, this is not considered to be a suitable surrogate for coated bleached paperboard foodservice products because of several important differences between coated magazine paper and coated paperboard foodservice products: (1) magazine paper contains groundwood pulp, which has a higher degree of lignin than foodservice paperboard, (2) magazine paper coating is clay, compared to resin coatings used on the paperboard foodservice products, and (3) approximately 1/3 of the weight of the coated magazine paper is coating, compared to a coating weight of 10 percent modeled for the paperboard foodservice products.

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).

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[18] 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 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 reactors were maintained at these conditions to maximize decomposition and monitored until no more methane was being produced. After 671 days of monitoring, the maximum degree of decomposition for the cellulose and hemicellulose fractions of office paper was 98 percent and 86 percent, respectively, based on material analysis of the residual material in the reactor at the end of the decomposition period. Overall, 41 percent by weight of the office paper degraded, based on the calculated carbon content of the cellulose and hemicellulose that decomposed. The remaining biomass carbon content of the paperboard did not degrade.

The quantities of methane recovered from decomposition of the various paper grades in the Barlaz experiments generally corresponded well with the theoretical amount of methane expected to be produced based on the carbon content of cellulose and hemicellulose and the observed degree of decomposition of the cellulose and hemicellulose fractions. However, this was not the case for office paper. The amount of methane recovered from the office paper reactor (155 g methane/kg of paper) was considerably lower than the amount of methane expected based on the amount of cellulose and hemicellulose that degraded (276 g methane/kg of paper). According to the Barlaz paper, it was not possible to determine the reason for the discrepancy between the amount of collected methane and the amount that should have been produced from the degraded material. As a result, there is uncertainty regarding the ultimate fate of the amount of carbon that degraded but did not produce methane. It is not clear whether this carbon was ultimately released or sequestered. Because of this uncertainty, the maximum methane emissions used in the end-of-life modeling for foodservice paperboard are based on the theoretical amount that should be produced from anaerobic decomposition of the amount of cellulose and hemicellulose that degraded in the landfill simulation experiment. End-of-life results based on the actual amounts of methane recovered from the experimental reactors are shown in the sensitivity analysis.

The composition of landfill gas as generated from anaerobic decomposition is approximately 50 percent by volume methane and 50 percent by volume CO_2.[19] The mass of methane generated from decomposition of a biomass-derived product is calculated based on the mass of carbon in the product that decomposes and the mass of methane generated, assuming 50 percent of the carbon that decomposes produces methane. 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 (10 percent of the methane that is not captured or flared) is oxidized as it travels through the landfill cover.[20]

[19] U.S. EPA. **Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006** (February 2008). Chapter 8, section 8.1 Landfills.

[20] Ibid.Calculated from 2006 data in Table 8-4.

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[21] indicates that the majority of landfill gas burned with energy recovery is used to produce electricity. The gross energy recovered from combustion of LF gas from each material is converted to displaced quantities of grid electricity using an efficiency factor of 1 kWh generated per 11,700 Btu of LF gas burned.[22] Each product system is credited with avoiding the CO_2 eq associated with production of the offset quantity of grid electricity.

For the carbon that remains fixed in the landfilled biomass-derived material (e.g., in the PLA resin and in the undecomposed portion of the paperboard foodservice products), a sequestration credit is given for the equivalent pounds of CO_2 that the sequestered carbon could produce.

Waste-to-energy combustion of postconsumer material is modeled using a similar approach to the landfill gas combustion credit. However, for WTE combustion of foodservice products, the CO_2 releases are modeled based on the *total* carbon content of the material oxidizing to CO_2. For combustion of paperboard and PLA, the CO_2 produced is considered carbon-neutral biomass CO_2, while the CO_2 from combustion of EPS and GPPS resin and LDPE coatings on paperboard products 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[23], and a credit is given for avoiding the CO_2 eq associated with producing the equivalent amount of grid electricity.

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

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

23 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 net end-of-life CO_2 eq for each product 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 foodservice products.

Limitations of End-of-Life Modeling Approach. As noted, the landfill methane calculations in this analysis are based on the *aggregated* emissions of methane that may result from decomposition of the degradable carbon content of the landfilled material. The long time frame over which those emissions occur has implications that result in additional uncertainties for the landfill methane CO_2 eq estimates.

- The length of time required for paperboard products to decompose will vary depending on landfill conditions and the effects of any coatings on the products that may inhibit or prevent decomposition. The global warming impacts of the total pounds of methane emissions released from decomposition are calculated using 100-year global warming potentials. In other words, regardless of the time frame over which decomposition occurs, the GWP calculation takes into account the global warming impacts of each pound of released methane in the atmosphere for 100 years after it has been released.
- 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, it is likely that efforts to mitigate global warming will result in increased efforts to capture and combust landfill methane. Combustion of biomass-derived methane converts the carbon back to CO_2, neutralizing the net global warming impact. In addition, when combustion energy is recovered and used to produce electricity, there are CO_2 eq 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 (from uncaptured, untreated methane emissions) to a net credit (for capturing landfill methane and burning it to produce energy with carbon-neutral CO_2 emissions, displacing fossil fuel combustion emissions).
- The percentage of methane that oxidizes as it passes through the landfill cover was calculated based on 2006 landfill methane data in the EPA's **Inventory of U.S. Greenhouse Gas Emissions and Sinks,** which uses the IPCC guideline of 10 percent as the default value for oxidation of landfill methane that is not captured or vented. However, some studies have suggested that a higher percentage of uncollected methane may oxidize as it migrates to the landfill surface.[24] The higher the percentage of uncollected methane that oxidizes in the landfill cover, the lower the CO_2 eq for landfilled paperboard products.

[24] Chanton, J. P.; Powelson, D. K.; Green, R.B. **Methane Oxidation in Landfill Cover Soils, is a 10% Default Value Reasonable?,** J Environ. Qual. 38:654-663 (2009).

Based on the uncertainties about degree of decomposition of paperboard products, the amount of methane produced from decomposition, and the fate of the generated methane, sensitivity analysis on end-of-life CO_2 eq for paperboard products is presented in Chapter 3.

Water Use

Although there is increasing emphasis on including water use in life cycle inventories, there is currently a lack of detailed water use data available for modeling on a unit process level. In addition, water use data that are available from different sources do not use a consistent method of distinguishing between consumptive use and non-consumptive use of water or clearly identifying the water sources used (freshwater versus saltwater, groundwater versus surface water). A recent article in the International Journal of Life Cycle Assessment summarized the status and deficiencies of water use data for LCA, including the statement, "To date, data availability on freshwater use proves to be a limiting factor for establishing meaningful water footprints of products."[25] A description of the water use research and data used in this analysis are presented in Appendix A.

System Components Not Included

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

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.

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.

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

Miscellaneous Materials and Additives. Selected materials such as catalysts, pigments, or other additives which total less than one percent by weight of the net process inputs are typically not included in the assessment unless inventory data for their production are readily available or there is reason to believe the materials would make significant contributions to energy use or environmental impacts. For example, some manufacturers of disposable foodservice items use inks and pigments to decorate their products. The production and application of inks and pigments were not included in the scope of this analysis.

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.

Indirect Land Use Change. Indirect land use change is defined as “the conversion of non-agricultural land to agricultural land as a consequence of changes in agricultural practice elsewhere” (PAS 2050). Indirect land use can be an important issue in LCAs that look at large shifts in uses of agricultural products (e.g., diversion of corn grain from food uses to produce biofuels) and attempt to evaluate the consequential effects on other systems outside the boundaries of the product systems being studied. For PLA products, there could be indirect land use changes if the use of corn as a feedstock for PLA reduced the available U.S. corn supply such that non-agricultural land had to be converted to agricultural use to make up for this. However, it is unclear whether there have been indirect land use changes that can be attributed to the use of corn for PLA production. Additionally, there are large uncertainties in projecting the types and locations of land that might be converted to agricultural use as a result of using a given quantity of corn as feedstock for PLA. The greenhouse gas emissions for indirect land use change can vary widely depending on assumptions about the type and location of land converted. Furthermore, this analysis is an attributional LCI, not a consequential LCI. As such, the analysis is based on the environmental burdens attributed to the products being studied and does not attempt to model the consequential effects on other systems.

CHAPTER 2

LIFE CYCLE INVENTORY RESULTS FOR DISPOSABLE FOODSERVICE PRODUCTS

INTRODUCTION

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

STUDY GOAL AND INTENDED USE

The goal of this study is to extend the scope of the 2006 PSPC LCI to include the following additions:

1. Production and disposal of available PLA products corresponding as closely as possible to the foodservice products in the original LCI,
2. Modeling of the carbon footprint implications of landfilling and waste-to-energy (WTE) incineration of the foodservice products from the original study and the PLA products,
3. Addition of water use to the life cycle inventory results.

The primary intended use of the study results is to provide PFPG with more complete information about the environmental burdens and greenhouse gas impacts from the life cycle of disposable foodservice products. A secondary intended use is public release of the study. The LCI has been conducted following internationally accepted standards for LCI methodology. Before the study is made publicly available, the completed report will be peer reviewed in accordance with ISO standards for life cycle assessment.

The results presented here for paperboard and PLA foodservice products are intended for benchmarking purposes only. Because this study was conducted without the direct participation of manufacturers of paperboard and PLA foodservice products, the results shown in this study should not be used to represent specific brands of these products available in the marketplace. Although the PLA modeling in this analysis is based on NatureWorks Ingeo™ data, it is not known whether the PLA product samples weighed for this analysis were manufactured from Ingeo brand PLA.

In addition, a key observation in the original PSPC foodservice study was that conclusions regarding the environmental profiles of foodservice products are dependent not only on the materials used but on the weights of the products. The results presented in this report are for the *average weight* polystyrene and paperboard products from the PSPC report and a limited number of samples of PLA products. Comparisons of products with different weights than the products studied in this analysis may yield different conclusions about the products' relative environmental profiles. Therefore, the results of this study should *not* be used to draw general conclusions about comparative results for the full range of products available in each product category.

SCOPE AND BOUNDARIES

This LCI encompasses the following steps in the life cycle of each foodservice product studied:

- Raw material extraction (e.g., extraction of petroleum and natural gas as feedstocks for EPS and GPPS resin, growing of corn used as feedstock for PLA production, harvesting of trees used for papermaking)
- Processing and fabrication steps to transform raw materials into finished products
- End-of-life management.

Transportation of products from manufacturing sites to retail stores is not included, nor does the analysis include the production and disposal of secondary packaging used to package products for shipment. Foodservice products are typically packaged in film sleeves, with several sleeves of products in a corrugated box. Because foamed products are thicker than coated paperboard products, the height of a stack of foam products is greater than the stacked height of an equivalent number of paperboard items. Therefore, a box of the same dimensions can hold a greater number of paperboard items than foam items. However, the greater density of paperboard products may require a sturdier (heavier) box compared to a box containing foam products. The contribution of secondary packaging to the overall results for foodservice products was evaluated in the original PSPC study.

The modeling for PLA production begins with corn growing. The NatureWorks PLA data set reported the amount of land required for production of 1 kg of PLA but did not provide details about any land use change impacts that may have been modeled. Because the PLA facility is supplied by corn from counties that have a history of corn production, it is expected that the land used to grow the corn was already in use for agricultural purposes and did not require converting land from its natural state.

End-of-life management options considered for the disposable foodservice products include landfilling and waste-to-energy combustion. According to recent U.S. EPA Municipal Solid Waste Facts and Figures reports, approximately 80 percent by weight of municipal solid waste that is not recovered for recycling or composting is managed by landfill and the other 20 percent by weight is managed by waste-to-energy (WTE) combustion. Although some of the products analyzed are recyclable or compostable, currently there is very little recycling or composting of the foodservice products studied in this analysis, so evaluation of composting or recycling of foodservice items is excluded from the scope of this analysis.

The results presented in this analysis include energy, solid waste (by weight and by volume), greenhouse gas emissions, and water use. The end-of-life greenhouse gas results include estimates of carbon dioxide from WTE combustion of postconsumer foodservice products, methane from decomposition of landfilled paperboard foodservice products, emission credits for avoided grid electricity displaced by electricity generated from WTE energy and landfill gas combustion, and carbon sequestration in landfilled biomass-derived material that does not decompose.

There are large uncertainties about the decomposition of landfilled paperboard foodservice products. Landfill simulation studies have not been run on coated paperboard foodservice products, so decomposition results for the paperboard content of the foodservice products are estimated based on experimental results for bleached paper, as described in the End of Life Management section of the Methodology chapter. The coatings on paperboard cups and plates may inhibit or prevent decomposition of the fiber content. Furthermore, there are variations in the moisture and temperature conditions in landfills, as well as variations in the management of landfill gas at individual sites. Therefore, it is not possible to define an average or most likely scenario for greenhouse gas impacts from landfilled paperboard foodservice products. This analysis presents results for maximum potential decomposition, 50% decomposition, and 0% decomposition to cover upper and lower bounds and an intermediate scenario for potential end-of-life GHG results.

FUNCTIONAL UNIT

In a life cycle study, products are compared on the basis of providing the same defined function (called the **functional unit**). The function of disposable foodservice products is to hold a serving of food or beverage for a single use application.

As in the original PSPC study, it should be recognized that there are differences in the strength of different plates and the insulating performance of different types of cups. In this analysis, products are compared on a one-to-one basis. This basis allows easy scaling to alternative scenarios such as use of nested non-insulated cups ("double-cupping") or use of more than one plate to support a heavy load of food.

In addition to the average weight high-grade plates from the original PSPC study, the plate figures in this analysis also include results for two **lighter weight** plates (a GPPS foam plate and an equivalent strength coated paperboard plate) from a 2009 LCI study.[26] Including the 2009 plate results serves two purposes: (1) to provide a comparison of two plates with equivalent strength, and (2) to illustrate the influence of product weight on LCI results.

SYSTEMS STUDIED

The following foodservice product categories are included in the analysis:

- 16-ounce hot cups (EPS foam, poly-coated paperboard with and without a corrugated sleeve, PLA-coated paperboard with and without a corrugated sleeve)
- 32-ounce cold cups (EPS foam, poly-coated paperboard, wax-coated paperboard, solid PLA)
- 9-inch high-grade plates (GPPS foam, poly-coated paperboard, bleached molded pulp, solid PLA)
- Sandwich-size clamshells (GPPS foam, corrugated paperboard, solid PLA)

For the most part, the products modeled in this analysis are based on the average weight products in the PSPC study. For the new category of PLA products, a literature search was conducted for published information on weights of PLA foodservice products, and product samples were ordered from several companies.

Although the goal of the study was to model PLA products that corresponded as closely as possible with the PSPC study foodservice products, no PLA foam products were found. Also, the properties of PLA are not suitable for hot cups to be made entirely from PLA, so a 16-ounce hot cup PLA-coated paperboard hot cup is evaluated. For the cold cup, plate, and clamshell applications, solid PLA products are analyzed.

For the cold cup application, no 32-ounce PLA cup samples were available; however, samples of 24-ounce PLA cups and solid PP cups were obtained from the same manufacturer. Two approaches were used to estimate the weight of a 32-ounce PLA cup. The first method was to use the weight of a 32-ounce PP cup sample and scale up the weight based on the ratios of the weights of the PLA and PP 24-oz cup samples. The second approach was to take the weight of the 32-ounce PP cup and scale it up based on the relative densities of PLA and PP resin. The report shows results for both PLA cup weight estimates.

[26] "Life Cycle Inventory of Foam and Coated Paperboard Plates" conducted by Franklin Associates, Ltd. for Pactiv, December 2009.

The weight of the PLA plate is based on the weight of a solid polystyrene plate scaled using the weight ratio of samples of PLA clamshells and same size solid PS clamshells. The weight of the sandwich-size clamshell is based on actual PLA clamshell samples. The product weights analyzed in this study are listed in Table 2-1, together with a brief description of the source of the weight data.

DATA SOURCES

The following data sources were used to model the systems:

- The 2006 PSPC study was used as the primary source of data on the polystyrene and coated paperboard products. Plastic resin data (PS, LDPE) are ACC industry average resin data revised by Franklin Associates in 2010. Plate fabrication data and the weight of resin coating on the plate were updated using data sets provided by a private company in 2008.
- For PLA products, cradle-to-PLA resin energy and material use were based on a rolled-up cradle-to-resin dataset for NatureWorks Ingeo PLA polymer published in the U.S. LCI Database in March 2010. Converting energy for solid PLA products was based on a 2006 European study.[27]
- Production and combustion of fuels and U.S. average grid electricity used for process and transportation energy in all processes are from the U.S. LCI database.
- Water use data were derived from other published LCI databases, including PlasticsEurope Ecoprofiles[28] and the Ecoinvent database. The Ingeo dataset provided data on water use for corn growing as well as process and cooling water used in PLA production processes.
- End-of-life modeling is based on U.S. EPA reports and the Environmental Science and Technology article cited earlier[29].

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27 **Comparative LCA of 4 Types of Drinking Cups Used at Events.** OVAM. 2006. Downloaded from http://www.natureworksllc.com/our-values-and-views/life-cycle-assessment/external-life-cycle-assessment-studies.aspx. PLA cup fabrication data in section 1.8.4.2, page 263.

28 Accessed at http://lca.plasticseurope.org/index.htm.

29 Barlaz, et al.

Table 2-1. Products Modeled

16 oz Hot Cups	**grams/ item**	**Source**	**Weight ratio compared to avg PS foam product**	**Wt range in 2006 study (g)**
EPS	4.7	average weight cup from 2006 PSPC study		4.4 - 5.0
LDPE-coated Paperboard	13.3	average weight cup from 2006 PSPC study	2.8 for cup only; 4.1 for cup + sleeve	12.3 - 15.0
PLA-coated Paperboard	12.7	average wt of 16 samples from one manufacturer	2.7 for cup only; 3.9 for cup + sleeve	N/A
Unbleached Corrug Sleeve	5.8	average weight cup sleeve from 2006 PSPC study		4.1 - 7.5

32 oz Cold Cups	**grams/ item**	**Source**	**Weight ratio compared to avg PS foam product**	**Wt range in 2006 study (g)**
EPS	8.8	average weight cup from 2006 PSPC study		8.1 - 10.0
LDPE-coated Paperboard	19.8	average weight cup from 2006 PSPC study	2.2	19.8 - 23.3
Wax-coated Paperboard	31.3	average weight cup from 2006 PSPC study (one producer)	3.5	
Solid PLA 1	35.0	estimated based on weight of a 32 oz PP cup (23.3 g) and the weight ratios of samples of 24 oz PLA and PP cups produced by the same manufacturer (1)	4.0	N/A
Solid PLA 2	32.4	estimated based on the weight of 32 oz PP cup and ratio of densities of PLA and PP (2)	3.7	N/A

9-inch Heavy Duty Plates	**grams/ item**	**Source**	**Weight ratio compared to avg PS foam product**	**Wt range in 2006 study (g)**
GPPS Foam	10.8	average weight plate from 2006 PSPC study		10.4 - 11.1
LDPE-coated Paperboard	18.4	average weight plate from 2006 PSPC study	1.7	18.2 - 18.5
Solid PLA	20.7	estimated based on weight of solid PS plate samples (18 g) and the weight ratio of solid PLA and solid PS clamshells produced by the same manufacturer (3)	1.9	N/A
Molded Pulp	16.6	average weight plate from 2006 PSPC study	1.5	16.2 - 17.4

9-inch Lightweight Plates	**grams/ item**	**Source**	**Weight ratio compared to avg PS foam product**
GPPS Foam	4.7	separate 2009 study	
Competing LDPE-coated Paperboard	12.1	separate 2009 study	2.6

Sandwich-size Clamshells	**grams/ item**	**Source**	**Weight ratio compared to avg PS foam product**	**Wt range in 2006 study (g)**
GPPS Foam	4.8	average weight clamshell from PSPC study		4.4 - 5.0
Fluted Paperboard	10.2	average weight clamshell from PSPC study	2.1	10.2 - 10.3
Solid PLA	23.3	average weight of actual samples of PLA clamshells obtained and weighed by Franklin Associates	4.9	N/A

(1) For samples of 24 oz PLA cups and 24 oz PP cups made by the same producer, the PLA cup was 50% heavier than the same size PP cup. This weight ratio was applied to the weight of a 32 oz PP cup (23.3 g) to estimate the weight of a 32 oz PLA cup (23.3 x 1.5 = 35.0 g).

(2) Using resin densities of 0.90 g/cm3 for PP and 1.25 g/cm3 for PLA, a product made of PLA would weigh 1.39 times as much as a product made of the equivalent volume of PP resin. 23.3 g PP cup x 1.25/0.9 = 32.4 g PLA cup.

(3) For samples of PLA clamshells and solid (non-foam) PS clamshells made by the same producer, the PLA clamshell was 15% heaver than the same size PS clamshell. This weight ratio was applied to the weight of a solid PS plate (18 g) to estimate the weight of the same size solid PLA plate (18 g PS plate x 1.15 = 20.7 g PLA plate).

Source: Franklin Associates, A Division of ERG.

For coated paperboard foodservice cups, the amount of coating is modeled as 10 percent of the weight of the product, the same assumption used in the peer-reviewed life cycle inventory study of foodservice products[30]. This assumption was validated by Franklin Associates based on published information on coated foodservice boardstock composition. The plate coating was modeled as approximately 8 percent by weight of the plate, based on information provided to Franklin Associates by a private company.

RESULTS

In addition to the energy, solid waste, and greenhouse gas emissions that were reported in the 2006 PSPC study, this report adds results for water use and end-of-life greenhouse gas emissions, expressed as pounds of carbon dioxide equivalents (CO_2 eq).

An important issue with LCI results is whether two numbers are actually different from one another. If the error or variability in the data is sufficiently large, it cannot be concluded that the two numbers are truly different. A statistical analysis that yields clear numerical answers would be ideal, but LCI data, which are typically based on a limited number of data sets for each unit process, are not suited to application of formal statistics, which pertain to random samples from large populations that result in "normal curve" distributions. However, based on the professional judgment of the analysts, the following guidance is provided for interpretation of LCI results presented in this report: In order for two systems' results to be considered significantly different, there must be a minimum percent difference of 10% in results for energy and postconsumer solid waste weight and 25% for emissions.[31]

Energy Results

The energy results presented in this report include not only the energy directly consumed in process and transportation steps, but also precombustion energy (the energy used to extract and process fuels used for process energy and transportation energy), and the energy content of resources used as material inputs to the product systems.

Total Energy by Category. Tables 2-2 through 2-5 present total energy results for each system broken out into the categories of process energy, transportation energy, and energy of material resource (EMR).

30 "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.

31 The percent difference between system results is calculated as the difference between the two systems' results divided by the average of the two systems' results.

The category of **process energy** includes totals for all processes required to produce each foodservice product, from acquisition of raw materials through manufacture of finished products, as well as operation of equipment used in landfilling postconsumer products. The end-of-life process energy shown in Tables 2-2 through 2-5 includes a credit for the energy recovered from waste-to-energy combustion of postconsumer items or recovered landfill gas. **Transportation energy** is the energy used to move material from location to location during its journey from raw material to finished product, and for collection and transport of postconsumer material. **Energy of material resource (EMR)** is the energy value of resources that are removed from the natural environment for use as material feedstocks for the product systems. EMR derived from fossil fuel resources and from biomass resources are shown separately in Tables 2-2 through 2-5. Some of the EMR remains embodied in the end product and can potentially be recovered depending on the ultimate fate of the postconsumer material. Energy can be recovered through WTE combustion of the material at the end of its useful life, or the energy content of the material can go with it into a landfill. The EMR shown in Tables 2-2 through 2-5 is the total EMR to produce the product. Adjustment for the EMR that remains in landfilled postconsumer products is included in the calculation of net expended energy shown in Tables 2-7 through 2-10. Energy of material resource is described in more detail in Chapter 1.

EMR accounts for 38 to 47 percent of total energy for the polystyrene foodservice products. For coated paperboard products, fossil EMR associated with polyethylene coatings represents 6 to 9 percent of total energy, and biomass EMR for the paperboard content is 21 to 31 percent of the total energy. For solid PLA products, biomass EMR comprises 31 to 36 percent of total energy requirements.

Transportation energy accounts for a small percentage of total energy for the systems, less than 5 percent. The remainder of the energy for each system is process energy. For the coated and uncoated paperboard systems, process energy accounts for 63 to 77 percent of the total energy requirements. Process energy ranges from 50 to 59 percent of the total energy for the PS systems, and 62 to 68 percent of total energy for solid PLA products.

Energy results by category are shown for the four categories of foodservice products in Figures 2-1a through 2-4a.

Table 2-2. Energy Results by Category for Average Weight 16-oz Hot Cups
(Million Btu per 10,000 cups)

	Process	Transp	Fossil EMR	Biomass EMR	Total
EPS foam cup (4.7 g)					
Cup production	4.20	0.15	2.63	0	6.98
End-of-life	-0.13	0.028	0	0	-0.10
Total	**4.07**	**0.18**	**2.63**	**0**	**6.88**
Percent by Category	**59.2%**	**2.5%**	**38.2%**	**0.0%**	**100.0%**
LDPE-coated ppbd cup (13.3 g), max decomp					
Cup production	6.31	0.21	0.78	1.82	9.11
End-of-life	-0.58	0.036	0	0	-0.55
Total	**5.73**	**0.25**	**0.78**	**1.82**	**8.57**
Percent by Category	**66.8%**	**2.9%**	**9.1%**	**21.2%**	**100.0%**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), max decomp					
Cup + sleeve production	7.93	0.30	0.78	2.70	11.7
End-of-life	-0.75	0.052	0	0	-0.70
Total	**7.18**	**0.35**	**0.78**	**2.70**	**11.0**
Percent by Category	**65.2%**	**3.2%**	**7.1%**	**24.5%**	**100.0%**
PLA-coated ppbd cup (12.7 g), max decomp					
Cup production	6.09	0.20	0.0013	2.04	8.33
End-of-life	-0.52	0.035	0	0	-0.49
Total	**5.56**	**0.23**	**0.0013**	**2.04**	**7.84**
Percent by Category	**71.0%**	**2.9%**	**0.0%**	**26.1%**	**100.0%**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), max decomp					
Cup + sleeve production	7.71	0.28	0.0014	2.93	10.9
End-of-life	-0.69	0.050	0	0	-0.64
Total	**7.02**	**0.33**	**0.0014**	**2.93**	**10.3**
Percent by Category	**68.3%**	**3.2%**	**0.0%**	**28.5%**	**100.0%**
LDPE-coated ppbd cup (13.3 g), 50% decomp					
Cup production	6.31	0.21	0.78	1.82	9.11
End-of-life	-0.43	0.036	0	0	-0.39
Total	**5.88**	**0.25**	**0.78**	**1.82**	**8.72**
Percent by Category	**67.4%**	**2.8%**	**8.9%**	**20.8%**	**100.0%**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), 50% decomp					
Cup + sleeve production	7.93	0.30	0.78	2.70	11.7
End-of-life	-0.56	0.052	0	0	-0.51
Total	**7.37**	**0.35**	**0.78**	**2.70**	**11.2**
Percent by Category	**65.8%**	**3.1%**	**6.9%**	**24.1%**	**100.0%**
PLA-coated ppbd cup (12.7 g), 50% decomp					
Cup production	6.09	0.20	0.0013	2.04	8.33
End-of-life	-0.37	0.035	0	0	-0.34
Total	**5.72**	**0.23**	**0.0013**	**2.04**	**7.99**
Percent by Category	**71.5%**	**2.9%**	**0.0%**	**25.6%**	**100.0%**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), 50% decomp					
Cup + sleeve production	7.71	0.28	0.0014	2.93	10.9
End-of-life	-0.50	0.050	0	0	-0.45
Total	**7.21**	**0.33**	**0.0014**	**2.93**	**10.5**
Percent by Category	**68.9%**	**3.2%**	**0.0%**	**28.0%**	**100.0%**
LDPE-coated ppbd cup (13.3 g), 0% decomp					
Cup production	6.31	0.21	0.78	1.82	9.11
End-of-life	-0.27	0.036	0	0	-0.24
Total	**6.04**	**0.25**	**0.78**	**1.82**	**8.88**
Percent by Category	**68.0%**	**2.8%**	**8.7%**	**20.5%**	**100.0%**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), 0% decomp					
Cup + sleeve production	7.93	0.30	0.78	2.70	11.7
End-of-life	-0.37	0.052	0	0	-0.32
Total	**7.56**	**0.35**	**0.78**	**2.70**	**11.4**
Percent by Category	**66.4%**	**3.1%**	**6.8%**	**23.7%**	**100.0%**
PLA-coated ppbd cup (12.7 g), 0% decomp					
Cup production	6.09	0.20	0.0013	2.04	8.33
End-of-life	-0.22	0.035	0	0	-0.19
Total	**5.87**	**0.23**	**0.0013**	**2.04**	**8.14**
Percent by Category	**72.1%**	**2.8%**	**0.0%**	**25.1%**	**100.0%**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), 0% decomp					
Cup production	7.71	0.28	0.0014	2.93	10.9
End-of-life	-0.32	0.050	0	0	-0.27
Total	**7.39**	**0.33**	**0.0014**	**2.93**	**10.7**
Percent by Category	**69.4%**	**3.1%**	**0.0%**	**27.5%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Table 2-3. Energy Results by Category for Average Weight 32-oz Cold Cups
(Million Btu per 10,000 cups)

	Process	Transp	Fossil EMR	Biomass EMR	Total
EPS foam cup (8.8 g)					
Cup production	7.47	0.27	4.87	0	12.6
End-of-life	-0.24	0.053	0	0	-0.19
Total	**7.22**	**0.33**	**4.87**	**0**	**12.4**
Percent by Category	**58.1%**	**2.6%**	**39.2%**	**0.0%**	**100.0%**
LDPE-coated ppbd cup (19.8 g), max decomp					
Cup production	9.97	0.35	1.05	3.06	14.4
End-of-life	-0.96	0.060	0	0	-0.90
Total	**9.02**	**0.41**	**1.05**	**3.06**	**13.5**
Percent by Category	**66.6%**	**3.0%**	**7.7%**	**22.6%**	**100.0%**
Wax-coated ppbd cup (31.3 g), max decomp					
Cup production	17.9	0.68	1.83	5.66	26.0
End-of-life	-1.75	0.085	0	0	-1.67
Total	**16.1**	**0.77**	**1.83**	**5.66**	**24.4**
Percent by Category	**66.1%**	**3.1%**	**7.5%**	**23.2%**	**100.0%**
Solid PLA cup, based on sample weights (35 g)					
Cup production	14.7	0.18	0.00	8.25	23.2
End-of-life	-0.68	0.095	0	0	-0.58
Total	**14.1**	**0.28**	**0.00**	**8.25**	**22.6**
Percent by Category	**62.3%**	**1.2%**	**0.0%**	**36.5%**	**100.0%**
Solid PLA cup, calculated using resin densities (32.4 g)					
Cup production	13.6	0.17	0.00	7.63	21.4
End-of-life	-0.63	0.088	0	0	-0.54
Total	**13.0**	**0.26**	**0.00**	**7.63**	**20.9**
Percent by Category	**62.3%**	**1.2%**	**0.0%**	**36.5%**	**100.0%**
LDPE-coated ppbd cup (19.8 g), 50% decomp					
Cup production	9.97	0.35	1.05	3.06	14.4
End-of-life	-0.70	0.060	0	0	-0.64
Total	**9.28**	**0.41**	**1.05**	**3.06**	**13.8**
Percent by Category	**67.3%**	**3.0%**	**7.6%**	**22.2%**	**100.0%**
Wax-coated ppbd cup (31.3 g), 50% decomp					
Cup production	17.9	0.68	1.83	5.66	26.0
End-of-life	-1.27	0.085	0	0	-1.19
Total	**16.6**	**0.77**	**1.83**	**5.66**	**24.9**
Percent by Category	**66.8%**	**3.1%**	**7.4%**	**22.8%**	**100.0%**
LDPE-coated ppbd cup (19.8 g), 0% decomp					
Cup production	9.97	0.35	1.05	3.06	14.4
End-of-life	-0.44	0.060	0	0	-0.38
Total	**9.54**	**0.41**	**1.05**	**3.06**	**14.0**
Percent by Category	**67.9%**	**2.9%**	**7.5%**	**21.7%**	**100.0%**
Wax-coated ppbd cup (31.3 g), 0% decomp					
Cup production	17.9	0.68	1.83	5.66	26.0
End-of-life	-0.79	0.085	0	0	-0.70
Total	**17.1**	**0.77**	**1.83**	**5.66**	**25.3**
Percent by Category	**67.4%**	**3.0%**	**7.2%**	**22.3%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Table 2-4. Energy Results by Category for Average Weight Heavy Duty 9-inch Plates
(Million Btu per 10,000 plates)

	Process	Transp	Fossil EMR	Biomass EMR	Total
GPPS foam plate (10.8 g)					
Plate production	6.24	0.25	5.51	0	12.0
End-of-life	-0.30	0.064	0	0	-0.23
Total	**5.94**	**0.31**	**5.51**	**0**	**11.8**
Percent by Category	**50.5%**	**2.7%**	**46.9%**	**0.0%**	**100.0%**
LDPE-coated plate (18.4 g), max decomp					
Plate production	9.03	0.29	0.75	2.60	12.7
End-of-life	-0.80	0.050	0	0	-0.75
Total	**8.23**	**0.34**	**0.75**	**2.60**	**11.9**
Percent by Category	**69.0%**	**2.9%**	**6.3%**	**21.8%**	**100.0%**
Molded pulp plate (16.6 g), max decomp					
Plate production	10.7	0.29	0.0019	2.69	13.7
End-of-life	-0.72	0.041	0	0	-0.68
Total	**9.99**	**0.33**	**0.0019**	**2.69**	**13.0**
Percent by Category	**76.8%**	**2.5%**	**0.0%**	**20.7%**	**100.0%**
Solid PLA plate (20.7 g)					
Plate production	8.73	0.11	0.000	4.88	13.7
End-of-life	-0.40	0.056	0	0	-0.34
Total	**8.32**	**0.16**	**0.000**	**4.88**	**13.4**
Percent by Category	**62.3%**	**1.2%**	**0.0%**	**36.5%**	**100.0%**
LDPE-coated plate (18.4 g), 50% decomp					
Plate production	9.03	0.29	0.75	2.60	12.7
End-of-life	-0.58	0.050	0	0	-0.53
Total	**8.45**	**0.34**	**0.75**	**2.60**	**12.1**
Percent by Category	**69.6%**	**2.8%**	**6.2%**	**21.4%**	**100.0%**
Molded pulp plate (16.6 g), 50% decomp					
Plate production	10.7	0.29	0.0019	2.69	13.7
End-of-life	-0.50	0.041	0	0	-0.46
Total	**10.2**	**0.33**	**0.0019**	**2.69**	**13.2**
Percent by Category	**77.2%**	**2.5%**	**0.0%**	**20.3%**	**100.0%**
LDPE-coated plate (18.4 g), 0% decomp					
Plate production	9.03	0.29	0.75	2.60	12.7
End-of-life	-0.36	0.050	0	0	-0.31
Total	**8.67**	**0.34**	**0.75**	**2.60**	**12.4**
Percent by Category	**70.1%**	**2.8%**	**6.1%**	**21.0%**	**100.0%**
Molded pulp plate (16.6 g), 0% decomp					
Plate production	10.7	0.29	0.0019	2.69	13.7
End-of-life	-0.29	0.041	0	0	-0.24
Total	**10.4**	**0.33**	**0.0019**	**2.69**	**13.4**
Percent by Category	**77.5%**	**2.4%**	**0.0%**	**20.0%**	**100.0%**
LIGHT-WEIGHT PLATES					
2009 GPPS Foam Plate (4.7 g)					
Plate production	2.71	0.11	2.40	0	5.22
End-of-life	-0.13	0.028	0	0	-0.10
Total	**2.58**	**0.14**	**2.40**	**0**	**5.12**
Percent by Category	**50.5%**	**2.7%**	**46.9%**	**0.0%**	**100.0%**
2009 LDPE-coated plate (12.1 g), equiv strength, max decomp					
Plate production	5.96	0.19	0.50	1.71	8.36
End-of-life	-0.53	0.033	0	0	-0.50
Total	**5.43**	**0.23**	**0.50**	**1.71**	**7.86**
Percent by Category	**69.0%**	**2.9%**	**6.3%**	**21.8%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Table 2-5. Energy Results by Category for Average Weight Sandwich-size Clamshells (Million Btu per 10,000 clamshells)

	Process	Transp	Fossil EMR	Biomass EMR	Total
GPPS foam clamshell (4.8 g)					
Clamshell production	2.89	0.11	2.45	0	5.45
End-of-life	-0.13	0.029	0	0	-0.10
Total	**2.75**	**0.14**	**2.45**	**0**	**5.34**
Percent by Category	**51.5%**	**2.6%**	**45.8%**	**0.0%**	**100.0%**
Fluted paperboard clamshell (10.2 g), max decomp					
Clamshell production	4.93	0.22	0.0011	2.22	7.38
End-of-life	-0.34	0.028	0	0	-0.32
Total	**4.59**	**0.25**	**0.0011**	**2.22**	**7.06**
Percent by Category	**65.0%**	**3.5%**	**0.0%**	**31.5%**	**100.0%**
Solid PLA clamshell (23.3 g)					
Clamshell production	12.5	0.12	0.00	5.50	18.2
End-of-life	-0.45	0.064	0	0	-0.39
Total	**12.1**	**0.18**	**0.00**	**5.50**	**17.8**
Percent by Category	**68.0%**	**1.0%**	**0.0%**	**30.9%**	**100.0%**
Fluted paperboard clamshell (10.2 g), 50% decomp					
Clamshell production	4.93	0.22	0.0011	2.22	7.38
End-of-life	-0.26	0.028	0	0	-0.23
Total	**4.68**	**0.25**	**0.0011**	**2.22**	**7.15**
Percent by Category	**65.4%**	**3.4%**	**0.0%**	**31.1%**	**100.0%**
Fluted paperboard clamshell (10.2 g), 0% decomp					
Clamshell production	4.93	0.22	0.0011	2.22	7.38
End-of-life	-0.17	0.028	0	0	-0.14
Total	**4.76**	**0.25**	**0.0011**	**2.22**	**7.23**
Percent by Category	**65.9%**	**3.4%**	**0.0%**	**30.7%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Figure 2-1a. Energy for 16-oz Hot Cups
(10,000 average weight cups)

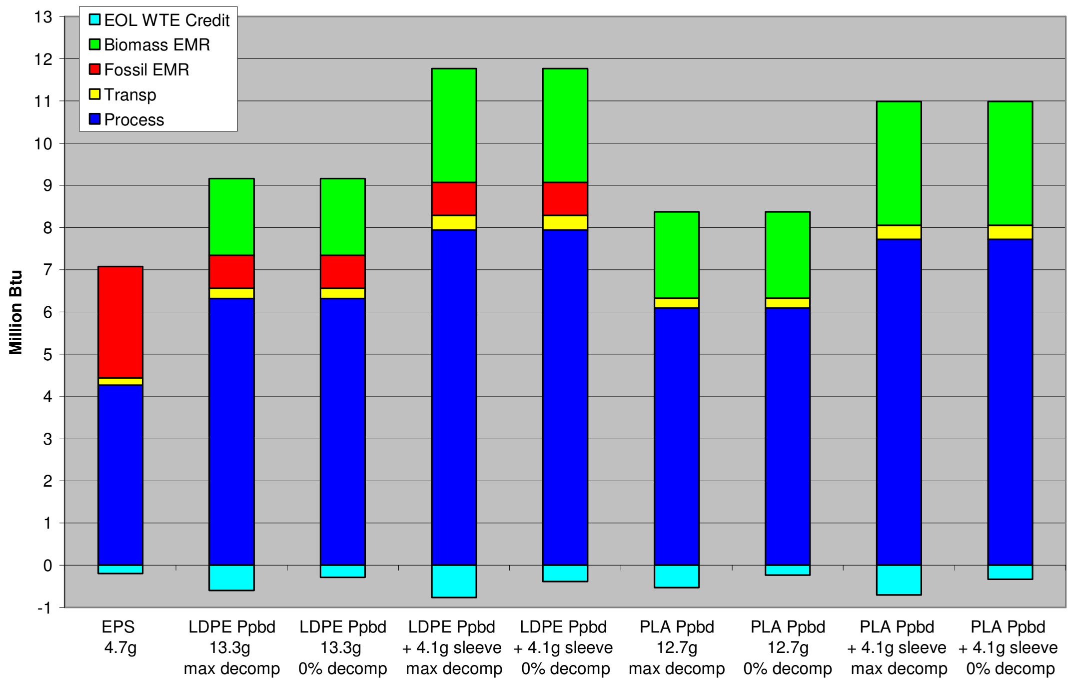


Figure 2-2a. Energy for 32-oz Cold Cups
(10,000 average weight cups)

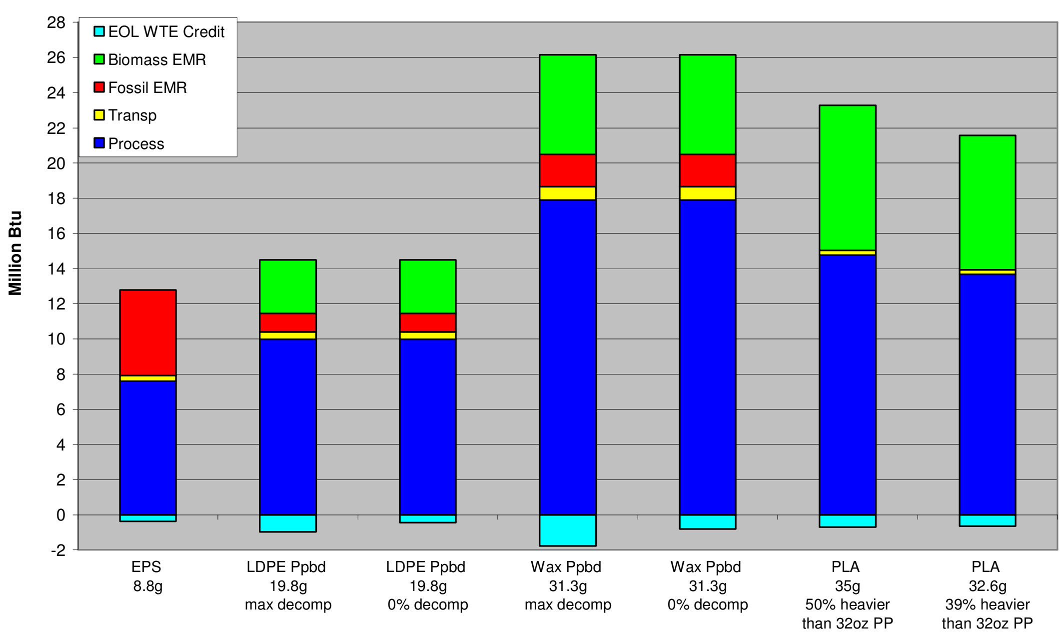


Figure 2-3a. Energy for 9-inch Plates
(10,000 average weight plates)

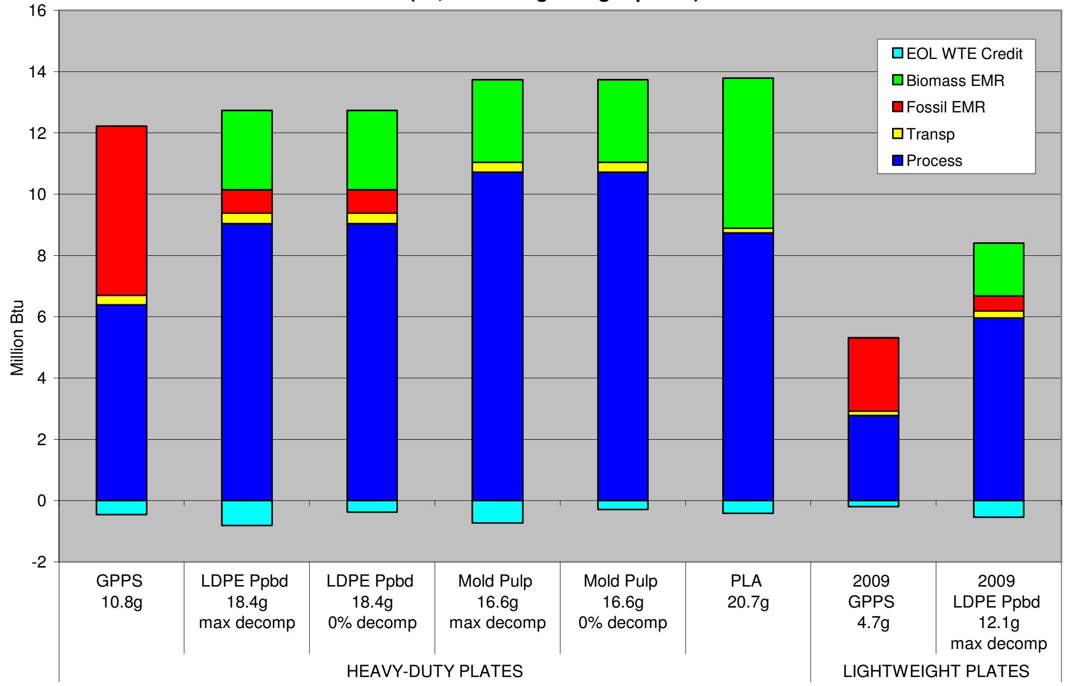
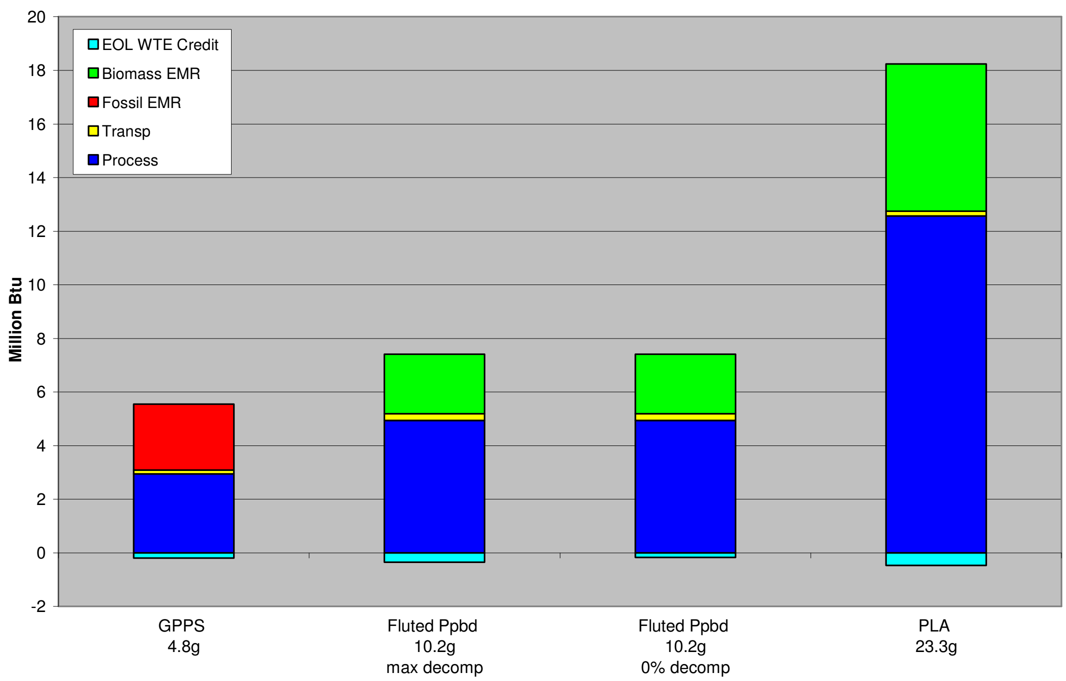


Figure 2-4a. Energy for Sandwich-size Clamshells
(10,000 average weight clamshells)



Net Energy Consumption. The energy requirements shown in Tables 2-2 through 2-5 reflect the *total* withdrawals from the energy pool required to produce each foodservice product. However, not all of this energy is actually expended. Tables 2-7 through 2-10 detail the adjustments to the total energy used to determine the *net* energy consumption for each foodservice product system. Energy of material resource plays a key role in the energy accounting.

As described in Chapter 1, the energy accounting methodology used in this report tracks the energy value of resources extracted from the natural environment for use as material feedstocks for the product systems. This energy value is referred to as energy of material resource (EMR) and is shown in Tables 2-2 through 2-5 under the headings “Fossil EMR” and “Biomass EMR”. Because of losses in processing and converting operations, the energy content of the end product is less than the energy value of the extracted resources; thus, there is some net expenditure of the EMR. However, some of the EMR remains embodied in the product (i.e., as the material’s higher heating value in Btu per pound). This is potentially recoverable energy rather than expended energy. Higher heating values for the materials used in the foodservice products are shown in Table 2-6.

In the first three columns of Tables 2-7 through 2-10, the total energy requirements are adjusted for the energy content of the products that are returned to the earth when 80 percent of postconsumer material is landfilled. The net expended energy (net energy consumption) for each system is calculated as the energy content of the resources extracted as material feedstock for the product, plus the process and transportation energy, minus the energy content in landfilled products, minus the energy recovered at end of life from combustion of products and combustion of recovered landfill gas from decomposition of landfilled products.

Table 2-6. HIGHER HEATING VALUES FOR MATERIALS IN FOODSERVICE PRODUCTS

	Higher Heating Value (Btu/lb)
EPS and GPPS	17,923
PLA	8,169
LDPE and wax coatings	19,968
Bleached paperboard	7,261
Corrugated sleeves and clamshells	7,047

Sources:
Thermodynamic Data for Biomass Materials and Waste Components. American Society of Mechanical Engineers. 1987.
Fire, Frank L. Combustibility of Plastics. Van Nostrand Reinhold. 1991.

Table 2-7. Net Energy Results for Average Weight 16-oz Hot Cups
(Million Btu per 10,000 cups)

	Total Energy (incl. EMR for biomass)	Energy Content of Material Landfilled*	Expended Energy	WTE & LF Gas Credit	Net Energy Consumption	Net % of Total
EPS foam cup (4.7 g)						
Cup production	6.98					
End-of-life	0.094	1.48		-0.20		
Total	**7.08**	**1.48**	**5.59**	**-0.20**	**5.40**	**76%**
LDPE-coated ppbd cup (13.3 g), max decomp						
Cup production	9.11					
End-of-life	0.046	2.03		-0.59		
Total	**9.16**	**2.03**	**7.13**	**-0.59**	**6.53**	**71%**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), max decomp						
Cup + sleeve production	11.7					
End-of-life	0.066	2.75		-0.76		
Total	**11.8**	**2.75**	**9.02**	**-0.76**	**8.26**	**70%**
PLA-coated ppbd cup (12.7 g), max decomp						
Cup production	8.33					
End-of-life	0.044	1.65		-0.53		
Total	**8.37**	**1.65**	**6.73**	**-0.53**	**6.20**	**74%**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), max decomp						
Cup + sleeve production	10.9					
End-of-life	0.063	2.36		-0.70		
Total	**11.0**	**2.36**	**8.62**	**-0.70**	**7.92**	**72%**
LDPE-coated ppbd cup (13.3 g), 50% decomp						
Cup production	9.11					
End-of-life	0.046	2.03		-0.44		
Total	**9.16**	**2.03**	**7.13**	**-0.44**	**6.69**	**73%**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), 50% decomp						
Cup + sleeve production	11.7					
End-of-life	0.066	2.75		-0.57		
Total	**11.8**	**2.75**	**9.02**	**-0.57**	**8.45**	**72%**
PLA-coated ppbd cup (12.7 g), 50% decomp						
Cup production	8.33					
End-of-life	0.044	1.65		-0.38		
Total	**8.37**	**1.65**	**6.73**	**-0.38**	**6.35**	**76%**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), 50% decomp						
Cup + sleeve production	10.9					
End-of-life	0.063	2.36		-0.52		
Total	**11.0**	**2.36**	**8.62**	**-0.52**	**8.11**	**74%**
LDPE-coated ppbd cup (13.3 g), 0% decomp						
Cup production	9.11					
End-of-life	0.046	2.03		-0.28		
Total	**9.16**	**2.03**	**7.13**	**-0.28**	**6.84**	**75%**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), 0% decomp						
Cup + sleeve production	11.7					
End-of-life	0.066	2.75		-0.38		
Total	**11.8**	**2.75**	**9.02**	**-0.38**	**8.64**	**73%**
PLA-coated ppbd cup (12.7 g), 0% decomp						
Cup production	8.33					
End-of-life	0.044	1.65		-0.23		
Total	**8.37**	**1.65**	**6.73**	**-0.23**	**6.50**	**78%**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), 0% decomp						
Cup production	10.9					
End-of-life	0.063	2.36		-0.33		
Total	**11.0**	**2.36**	**8.62**	**-0.33**	**8.29**	**76%**

* Represents amount of energy of material resource that remains in landfilled materials. This is calculated as the higher heating value of each material multiplied by the pounds landfilled (80% of the postconsumer material).

Source: Franklin Associates, A Division of ERG

Table 2-8. Net Energy Results for Average Weight 32-oz Cold Cups
(Million Btu per 10,000 cups)

	Total Energy (incl. EMR for biomass)	Energy Content of Material Landfilled*	Expended Energy	WTE & LF Gas Credit	Net Energy Consumption	Net % of Total
EPS foam cup (8.8 g)						
Cup production	12.6					
End-of-life	0.18	2.79		-0.37		
Total	**12.8**	**2.79**	**10.0**	**-0.37**	**9.63**	**75%**
LDPE-coated ppbd cup (19.8 g), max decomp						
Cup production	14.4					
End-of-life	0.075	3.25		-0.97		
Total	**14.5**	**3.25**	**11.3**	**-0.97**	**10.3**	**71%**
Wax-coated ppbd cup (31.3 g), max decomp						
Cup production	26.0					
End-of-life	0.11	5.82		-1.78		
Total	**26.2**	**5.82**	**20.3**	**-1.78**	**18.6**	**71%**
Solid PLA cup, based on sample weights (35 g)						
Cup production	23.2					
End-of-life	0.12	5.03		-0.70		
Total	**23.3**	**5.03**	**18.2**	**-0.70**	**17.5**	**75%**
Solid PLA cup, calculated using resin densities (32.4 g)						
Cup production	21.4					
End-of-life	0.111	4.66		-0.65		
Total	**21.6**	**4.66**	**16.9**	**-0.65**	**16.2**	**75%**
LDPE-coated ppbd cup (19.8 g), 50% decomp						
Cup production	14.4					
End-of-life	0.075	3.25		-0.71		
Total	**14.5**	**3.25**	**11.3**	**-0.71**	**10.5**	**73%**
Wax-coated ppbd cup (31.3 g), 50% decomp						
Cup production	26.0					
End-of-life	0.11	5.82		-1.29		
Total	**26.2**	**5.82**	**20.3**	**-1.29**	**19.0**	**73%**
LDPE-coated ppbd cup (19.8 g), 0% decomp						
Cup production	14.4					
End-of-life	0.075	3.25		-0.45		
Total	**14.5**	**3.25**	**11.3**	**-0.45**	**10.8**	**74%**
Wax-coated ppbd cup (31.3 g), 0% decomp						
Cup production	26.0					
End-of-life	0.11	5.82		-0.81		
Total	**26.2**	**5.82**	**20.3**	**-0.81**	**19.5**	**75%**

* Represents amount of energy of material resource that remains in landfilled materials. This is calculated as the higher heating value of each material multiplied by the pounds landfilled (80% of the postconsumer material).

Source: Franklin Associates, A Division of ERG

Table 2-9. Net Energy Results for Average Weight Heavy Duty 9-inch Plates
(Million Btu per 10,000 plates)

	Total Energy (incl. EMR for biomass)	Energy Content of Material Landfilled*	Expended Energy	WTE & LF Gas Credit	Net Energy Consumption	Net % of Total
GPPS foam plate (10.8 g)						
Plate production	12.0					
End-of-life	0.22	3.41		-0.45		
Total	**12.2**	**3.41**	**8.81**	**-0.45**	**8.36**	**68%**
LDPE-coated plate (18.4 g), max decomp						
Plate production	12.7					
End-of-life	0.063	2.67		-0.81		
Total	**12.7**	**2.67**	**10.1**	**-0.81**	**9.26**	**73%**
Molded pulp plate (16.6 g), max decomp						
Plate production	13.7					
End-of-life	0.052	2.13		-0.73		
Total	**13.7**	**2.13**	**11.6**	**-0.73**	**10.9**	**79%**
Solid PLA plate (20.7 g)						
Plate production	13.7					
End-of-life	0.071	2.98		-0.42		
Total	**13.8**	**2.98**	**10.8**	**-0.42**	**10.4**	**75%**
LDPE-coated plate (18.4 g), 50% decomp						
Plate production	12.7					
End-of-life	0.063	2.67		-0.59		
Total	**12.7**	**2.67**	**10.1**	**-0.59**	**9.48**	**74%**
Molded pulp plate (16.6 g), 50% decomp						
Plate production	13.7					
End-of-life	0.052	2.13		-0.51		
Total	**13.7**	**2.13**	**11.6**	**-0.51**	**11.1**	**81%**
LDPE-coated plate (18.4 g), 0% decomp						
Plate production	12.7					
End-of-life	0.063	2.67		-0.37		
Total	**12.7**	**2.67**	**10.1**	**-0.37**	**9.70**	**76%**
Molded pulp plate (16.6 g), 0% decomp						
Plate production	13.7					
End-of-life	0.052	2.13		-0.30		
Total	**13.7**	**2.13**	**11.6**	**-0.30**	**11.3**	**82%**
LIGHT-WEIGHT PLATES						
2009 GPPS Foam Plate (4.7 g)						
Plate production	5.22					
End-of-life	0.094	1.48		-0.20		
Total	**5.32**	**1.48**	**3.83**	**-0.20**	**3.64**	**68%**
2009 LDPE-coated plate (12.1 g), equiv strength, max decomp						
Plate production	8.36					
End-of-life	0.042	1.76		-0.54		
Total	**8.40**	**1.76**	**6.64**	**-0.54**	**6.10**	**73%**

* Represents amount of energy of material resource that remains in landfilled materials. This is calculated as the higher heating value of each material multiplied by the pounds landfilled (80% of the postconsumer material).

Source: Franklin Associates, A Division of ERG

Table 2-10. Net Energy Results for Average Weight Sandwich-size Clamshells
(Million Btu per 10,000 clamshells)

	Total Energy (incl. EMR for biomass)	Energy Content of Material Landfilled*	Expended Energy	WTE & LF Gas Credit	Net Energy Consumption	Net % of Total
GPPS foam clamshell (4.8 g)						
Clamshell production	5.45					
End-of-life	0.096	1.52		-0.20		
Total	**5.54**	**1.52**	**4.03**	**-0.20**	**3.83**	**69%**
Fluted paperboard clamshell (10.2 g), max decomp						
Clamshell production	7.38					
End-of-life	0.035	1.28		-0.35		
Total	**7.41**	**1.28**	**6.13**	**-0.35**	**5.78**	**78%**
Solid PLA clamshell (23.3 g)						
Clamshell production	18.2					
End-of-life	0.080	3.35		-0.47		
Total	**18.2**	**3.35**	**14.9**	**-0.47**	**14.4**	**79%**
Fluted paperboard clamshell (10.2 g), 50% decomp						
Clamshell production	7.38					
End-of-life	0.035	1.28		-0.26		
Total	**7.41**	**1.28**	**6.13**	**-0.26**	**5.86**	**79%**
Fluted paperboard clamshell (10.2 g), 0% decomp						
Clamshell production	7.38					
End-of-life	0.035	1.28		-0.18		
Total	**7.41**	**1.28**	**6.13**	**-0.18**	**5.95**	**80%**

* Represents amount of energy of material resource that remains in landfilled materials. This is calculated as the higher heating value of each material multiplied by the pounds landfilled (80% of the postconsumer material).

Source: Franklin Associates, A Division of ERG

Tables 2-7 through 2-10 also include adjustments for end-of-life energy recovery for each foodservice product system. The "WTE and LF Gas Credit" column shows the energy credit for the useful energy recovered through WTE combustion of the 20 percent of postconsumer products that are managed by this method, as well as a credit for WTE combustion of landfill methane recovered from decomposition of the paperboard and coated paperboard products. The gross heat of combustion is adjusted for the efficiency of converting the heat to useful electricity. The end-of-life recovered energy is subtracted from the expended energy to calculate the net energy consumption for each system.

The final columns in Tables 2-7 through 2-10 show that the net energy for polystyrene foodservice products is 24 to 32 percent less than the total energy requirements to produce the products. For paperboard and coated paperboard, net energy is 22 to 30 percent lower than total energy, while net energy for solid PLA products is 21 to 25 percent lower than total energy. Net energy is shown in Figures 2-1b through 2-4b. In the net energy figures, results for the PS systems are identified using red, while results for other materials are shown in blue.

Figure 2-1b. Net Energy for 16-oz Hot Cups
(10,000 average weight cups)

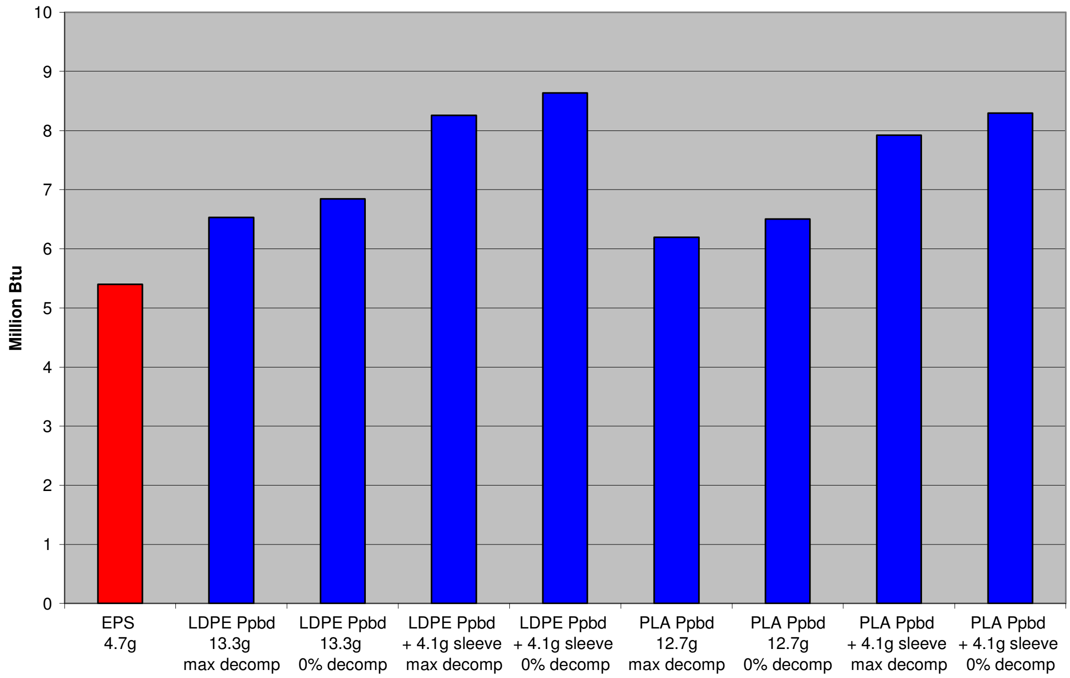


Figure 2-2b. Net Energy for 32-oz Cold Cups
(10,000 average weight cups)

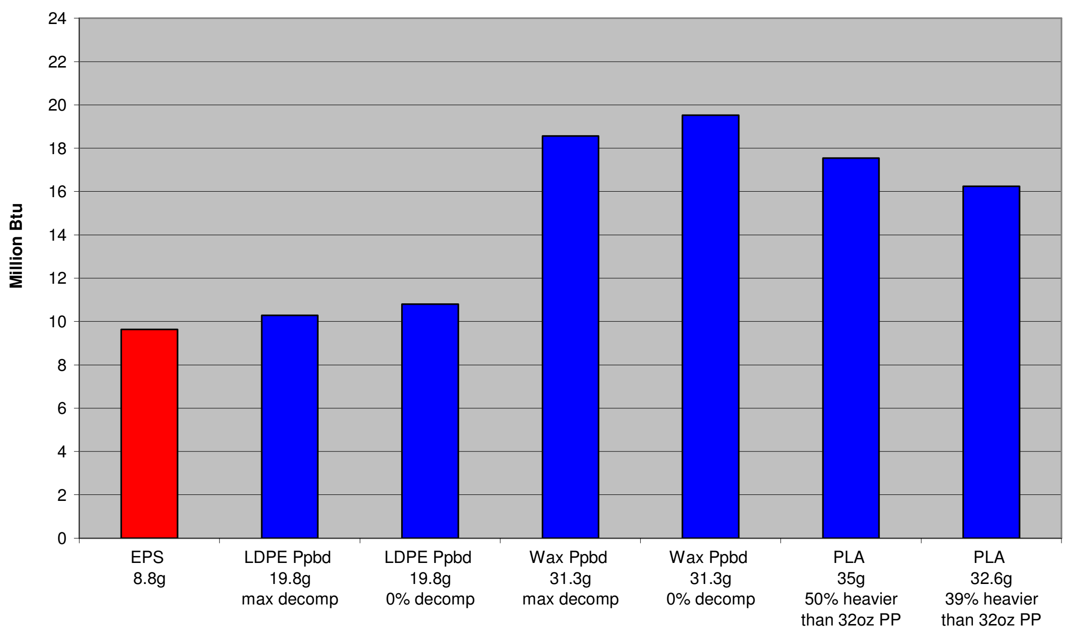


Figure 2-3b. Net Energy for 9-inch Plates
(10,000 average weight plates)

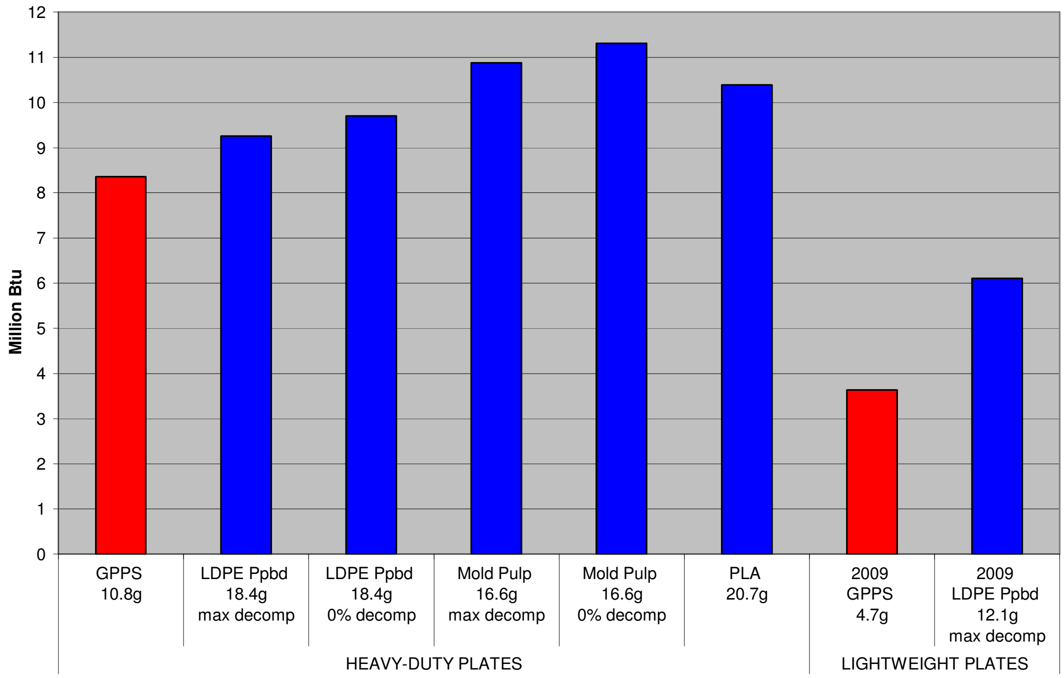
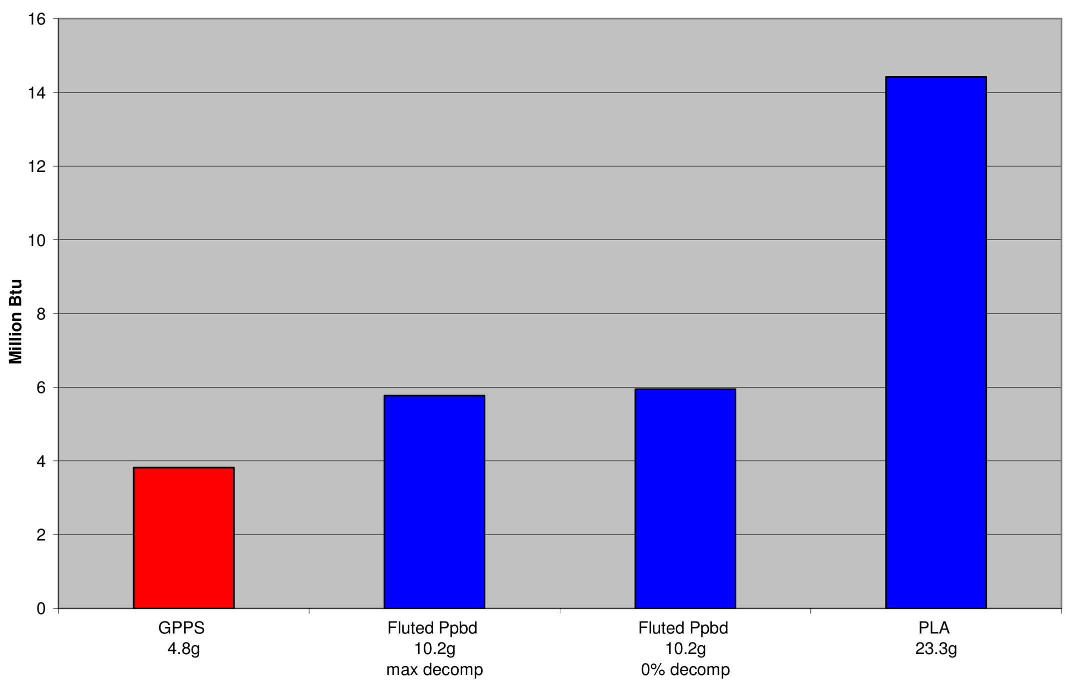


Figure 2-4b. Net Energy for Sandwich-size Clamshells
(10,000 average weight clamshells)



Fossil and Non-Fossil Energy. Fossil fuels – natural gas, petroleum and coal – are used for direct combustion as process and transportation fuels and also are used to generate over 70 percent of the purchased electricity in the United States. Petroleum is also the dominant energy source for transportation. The use of natural gas and petroleum as raw material inputs for the production of plastics (reported as fossil EMR in Tables 2-2 through 2-5) is included in the totals for fossil energy shown in Tables 2-11 through 2-14. The non-fossil energy shown in the tables includes process energy (e.g., wood-derived energy at paper mills, use of hydropower, nuclear, and wind energy to produce grid electricity) as well as the biomass EMR for paperboard and PLA products. Tables 2-11 through 2-14 do *not* include adjustment for the energy content remaining in the products landfilled at end of life.

For the polystyrene systems, over 95 percent of total energy is fossil energy. This includes not only the use of fossil fuels as process and transportation fuel but also the EMR of the resin material. For paperboard product systems, fossil energy accounts for a much lower share of total energy, about 28 to 37 percent of the total. In addition to the biomass EMR in the paper products, virgin paper mills utilize wood wastes as a fuel source, reducing their use of fossil fuels. For solid PLA products, 56 to 63 percent of total energy is fossil energy. Although the EMR for PLA is from biomass, process energy for PLA products is derived mainly from fossil fuels.

Table 2-11. Fossil and Non-fossil Energy Results for Average Weight 16-oz Hot Cups (Million Btu per 10,000 cups)

	Fossil	Non-Fossil	Total
EPS foam cup (4.7 g)			
Cup production	6.67	0.31	6.98
End-of-life	-0.067	-0.034	-0.10
Total	**6.60**	**0.28**	**6.88**
	96.0%	**4.0%**	**100.0%**
LDPE-coated ppbd cup (13.3 g), max decomp			
Cup production	3.49	5.62	9.11
End-of-life	-0.44	-0.11	-0.55
Total	**3.06**	**5.51**	**8.57**
	35.7%	**64.3%**	**100.0%**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), max decomp			
Cup + sleeve production	4.51	7.20	11.7
End-of-life	-0.55	-0.14	-0.70
Total	**3.95**	**7.05**	**11.0**
	35.9%	**64.1%**	**100.0%**
PLA-coated ppbd cup (12.7 g), max decomp			
Cup production	2.53	5.80	8.33
End-of-life	-0.39	-0.10	-0.49
Total	**2.14**	**5.70**	**7.84**
	27.3%	**72.7%**	**100.0%**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), max decomp			
Cup + sleeve production	3.55	7.37	10.9
End-of-life	-0.51	-0.13	-0.64
Total	**3.04**	**7.24**	**10.3**
	29.6%	**70.4%**	**100.0%**
LDPE-coated ppbd cup (13.3 g), 50% decomp			
Cup production	3.49	5.62	9.11
End-of-life	-0.31	-0.082	-0.39
Total	**3.18**	**5.54**	**8.72**
	36.5%	**63.5%**	**100.0%**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), 50% decomp			
Cup + sleeve production	4.51	7.20	11.7
End-of-life	-0.40	-0.11	-0.51
Total	**4.11**	**7.09**	**11.2**
	36.7%	**63.3%**	**100.0%**
PLA-coated ppbd cup (12.7 g), 50% decomp			
Cup production	2.53	5.80	8.33
End-of-life	-0.27	-0.071	-0.34
Total	**2.27**	**5.73**	**7.99**
	28.3%	**71.7%**	**100.0%**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), 50% decomp			
Cup + sleeve production	3.55	7.37	10.9
End-of-life	-0.36	-0.096	-0.45
Total	**3.19**	**7.28**	**10.5**
	30.5%	**69.5%**	**100.0%**
LDPE-coated ppbd cup (13.3 g), 0% decomp			
Cup production	3.49	5.62	9.11
End-of-life	-0.19	-0.053	-0.24
Total	**3.31**	**5.57**	**8.88**
	37.3%	**62.7%**	**100.0%**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), 0% decomp			
Cup + sleeve production	4.51	7.20	11.7
End-of-life	-0.25	-0.071	-0.32
Total	**4.26**	**7.13**	**11.4**
	37.4%	**62.6%**	**100.0%**
PLA-coated ppbd cup (12.7 g), 0% decomp			
Cup production	2.53	5.80	8.33
End-of-life	-0.14	-0.043	-0.19
Total	**2.39**	**5.76**	**8.14**
	29.3%	**70.7%**	**100.0%**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), 0% decomp			
Cup production	3.55	7.37	10.9
End-of-life	-0.20	-0.061	-0.27
Total	**3.34**	**7.31**	**10.7**
	31.4%	**68.6%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Table 2-12. Fossil and Non-fossil Energy Results for Average Weight 32-oz Cold Cups (Million Btu per 10,000 cups)

	Fossil	Non-Fossil	Total
EPS foam cup (8.8 g)			
Cup production	12.1	0.54	12.6
End-of-life	-0.13	-0.065	-0.19
Total	**11.9**	**0.48**	**12.4**
	96.2%	**3.8%**	**100.0%**
LDPE-coated ppbd cup (19.8 g), max decomp			
Cup production	5.07	9.36	14.4
End-of-life	-0.72	-0.18	-0.90
Total	**4.35**	**9.18**	**13.5**
	32.2%	**67.8%**	**100.0%**
Wax-coated ppbd cup (31.3 g), max decomp			
Cup production	8.69	17.4	26.0
End-of-life	-1.34	-0.33	-1.67
Total	**7.35**	**17.0**	**24.4**
	30.2%	**69.8%**	**100.0%**
Solid PLA cup, based on sample weights (35 g)			
Cup production	13.1	10.0	23.2
End-of-life	-0.45	-0.13	-0.58
Total	**12.7**	**09.9**	**22.6**
	56.1%	**43.9%**	**100.0%**
Solid PLA cup, calculated using resin densities (32.4 g)			
Cup production	12.1	9.30	21.4
End-of-life	-0.42	-0.12	-0.54
Total	**11.7**	**9.18**	**20.9**
	56.1%	**43.9%**	**100.0%**
LDPE-coated ppbd cup (19.8 g), 50% decomp			
Cup production	5.07	9.36	14.4
End-of-life	-0.50	-0.13	-0.64
Total	**4.56**	**9.23**	**13.8**
	33.1%	**66.9%**	**100.0%**
Wax-coated ppbd cup (31.3 g), 50% decomp			
Cup production	8.69	17.4	26.0
End-of-life	-0.94	-0.24	-1.19
Total	**7.74**	**17.1**	**24.9**
	31.1%	**68.9%**	**100.0%**
LDPE-coated ppbd cup (19.8 g), 0% decomp			
Cup production	5.07	9.36	14.4
End-of-life	-0.29	-0.084	-0.38
Total	**4.77**	**9.28**	**14.0**
	34.0%	**66.0%**	**100.0%**
Wax-coated ppbd cup (31.3 g), 0% decomp			
Cup production	8.69	17.4	26.0
End-of-life	-0.55	-0.15	-0.70
Total	**8.13**	**17.2**	**25.3**
	32.1%	**67.9%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Table 2-13. Fossil and Non-fossil Energy Results for Average Weight Heavy Duty 9-inch Plates (Million Btu per 10,000 plates)

	Fossil	Non-Fossil	Total
GPPS foam plate (10.8 g)			
Plate production	11.5	0.45	12.0
End-of-life	-0.15	-0.079	-0.23
Total	**11.4**	**0.37**	**11.8**
	96.8%	**3.2%**	**100.0%**
LDPE-coated plate (18.4 g), max decomp			
Plate production	4.63	8.05	12.7
End-of-life	-0.60	-0.15	-0.75
Total	**4.03**	**7.90**	**11.9**
	33.8%	**66.2%**	**100.0%**
Molded pulp plate (16.6 g), max decomp			
Plate production	5.36	8.32	13.7
End-of-life	-0.54	-0.14	-0.68
Total	**4.82**	**8.18**	**13.0**
	37.1%	**62.9%**	**100.0%**
Solid PLA plate (20.7 g)			
Plate production	7.77	5.95	13.7
End-of-life	-0.27	-0.077	-0.34
Total	**7.50**	**5.87**	**13.4**
	56.1%	**43.9%**	**100.0%**
LDPE-coated plate (18.4 g), 50% decomp			
Plate production	4.63	8.05	12.7
End-of-life	-0.42	-0.11	-0.53
Total	**4.21**	**7.94**	**12.1**
	34.6%	**65.4%**	**100.0%**
Molded pulp plate (16.6 g), 50% decomp			
Plate production	5.36	8.32	13.7
End-of-life	-0.37	-0.10	-0.46
Total	**5.00**	**8.23**	**13.2**
	37.8%	**62.2%**	**100.0%**
LDPE-coated plate (18.4 g), 0% decomp			
Plate production	4.63	8.05	12.7
End-of-life	-0.24	-0.069	-0.31
Total	**4.39**	**7.98**	**12.4**
	35.5%	**64.5%**	**100.0%**
Molded pulp plate (16.6 g), 0% decomp			
Plate production	5.36	8.32	13.7
End-of-life	-0.19	-0.055	-0.24
Total	**5.17**	**8.27**	**13.4**
	38.5%	**61.5%**	**100.0%**
LIGHT-WEIGHT PLATES			
2009 GPPS Foam Plate (4.7 g)			
Plate production	5.03	0.20	5.22
End-of-life	-0.067	-0.034	-0.10
Total	**4.96**	**0.16**	**5.12**
	96.8%	**3.2%**	**100.0%**
2009 LDPE-coated plate (12.1 g), equiv strength, max decomp			
Plate production	3.05	5.31	8.36
End-of-life	-0.40	-0.10	-0.50
Total	**2.66**	**5.21**	**7.86**
Percent by Category	**33.8%**	**66.2%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Table 2-14. Fossil and Non-fossil Energy Results for Average Weight Sandwich-size Clamshells (Million Btu per 10,000 clamshells)

	Fossil	Non-Fossil	Total
GPPS foam clamshell (4.8 g)			
Clamshell production	5.20	0.25	5.45
End-of-life	-0.069	-0.035	-0.10
Total	**5.13**	**0.21**	**5.34**
	96.0%	**4.0%**	**100.0%**
Fluted paperboard clamshell (10.2 g), max decomp			
Clamshell production	2.53	4.84	7.38
End-of-life	-0.25	-0.065	-0.32
Total	**2.28**	**4.78**	**7.06**
	32.3%	**67.7%**	**100.0%**
Solid PLA clamshell (23.3 g)			
Clamshell production	11.5	6.70	18.2
End-of-life	-0.30	-0.087	-0.39
Total	**11.2**	**6.62**	**17.8**
	62.8%	**37.2%**	**100.0%**
Fluted paperboard clamshell (10.2 g), 50% decomp			
Clamshell production	2.53	4.84	7.38
End-of-life	-0.18	-0.049	-0.23
Total	**2.35**	**4.79**	**7.15**
	32.9%	**67.1%**	**100.0%**
Fluted paperboard clamshell (10.2 g), 0% decomp			
Clamshell production	2.53	4.84	7.38
End-of-life	-0.11	-0.033	-0.14
Total	**2.42**	**4.81**	**7.23**
	33.5%	**66.5%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Solid Waste

Based on the uncertainty in solid waste data, differences in solid waste **weight** 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. The landfill density factors used to convert solid waste weights to volume are more uncertain, so a minimum 25 percent difference is required to consider solid waste **volume** results significantly different.

Solid waste is broadly categorized into process wastes, fuel-related wastes, and postconsumer wastes. **Process wastes** are the solid wastes generated by the various processes from raw material acquisition through fabrication of foodservice products, including any unrecycled fabrication scrap. **Fuel-related wastes** are the wastes from the production and combustion of fuels used for process energy and transportation energy. **Postconsumer wastes** are the products that are landfilled at end of life. This category also includes any ash resulting from waste-to-energy combustion of 20 percent of foodservice items.

Weight of Solid Waste. Solid waste results by weight are shown in Tables 2-15 through 2-18. The tables show the quantity of solid waste by type as well as the contributions of production and end-of-life management to the total. Figures 2-5 through 2-8 show the weight of solid wastes for each product system by category.

Postconsumer products account for the largest share of the weight of solid waste for all systems, from 63 to 79 percent of the total weight of solid waste. Since the majority of the solid waste for each system is postconsumer product, and the average weight polystyrene foam products are lighter than the coated paperboard and solid PLA products analyzed, the PS foam products have a lower total weight of solid waste compared to the alternative products.

The remainder of the solid waste is process and fuel-related wastes from production of the foodservice items. Fuel-related solid waste ranges from 16 to 26 percent of total solid waste for polystyrene foam systems and 22 to 27 percent of the total for solid PLA products. For paperboard product systems, fuel-related solid wastes make up 15 to 25 percent of the total solid waste. Paperboard products have the highest percentage of process solid waste, ranging from 8 to 13 percent of the total weight of solid waste. Process solid wastes are about 4 percent of total solid waste for the polystyrene systems and less than 1 percent for solid PLA products.

Table 2-15. Solid Waste by Weight for Average Weight 16-oz Hot Cups
(Pounds per 10,000 cups)

	Process	Fuel	Postconsumer (LF + WTE ash)	Total	Percent by Stage
EPS foam cup (4.7 g)					
Cup production	4.58	33.6	0	38.2	32.6%
End-of-life	0	-3.73	82.8	79.1	67.4%
Total	**4.58**	**29.9**	**82.8**	**117**	
Percent by Category	**3.9%**	**25.5%**	**70.6%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (13.3 g), max decomp					
Cup production	42.7	68.5	0	111	33.1%
End-of-life	0	-10.9	235	224	66.9%
Total	**42.7**	**57.6**	**235**	**336**	
Percent by Category	**12.7%**	**17.2%**	**70.1%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), max decomp					
Cup + sleeve production	55.6	92.5	0	148	31.4%
End-of-life	0	-13.9	338	324	68.6%
Total	**55.6**	**78.6**	**338**	**472**	
Percent by Category	**11.8%**	**16.6%**	**71.6%**	**100.0%**	**100.0%**
PLA-coated ppbd cup (12.7 g), max decomp					
Cup production	40.9	69.1	0	110.0	33.9%
End-of-life	0	-9.75	225	215	66.1%
Total	**40.9**	**59.4**	**225**	**325**	
Percent by Category	**12.6%**	**18.3%**	**69.1%**	**100.0%**	**100.0%**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), max decomp					
Cup + sleeve production	53.7	93.2	0	147	31.8%
End-of-life	0	-12.8	327	315	68.2%
Total	**53.7**	**80.4**	**327**	**461**	
Percent by Category	**11.6%**	**17.4%**	**70.9%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (13.3 g), 50% decomp					
Cup production	42.7	68.5	0	111	32.9%
End-of-life	0	-8.00	235	227	67.1%
Total	**42.7**	**60.5**	**235**	**338**	
Percent by Category	**12.6%**	**17.9%**	**69.5%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), 50% decomp					
Cup + sleeve production	55.6	92.5	0	148	31.1%
End-of-life	0	-10.4	338	327	68.9%
Total	**55.6**	**82.1**	**338**	**476**	
Percent by Category	**11.7%**	**17.3%**	**71.1%**	**100.0%**	**100.0%**
PLA-coated ppbd cup (12.7 g), 50% decomp					
Cup production	40.9	69.1	0	110.0	33.6%
End-of-life	0	-6.95	225	218	66.4%
Total	**40.9**	**62.2**	**225**	**328**	
Percent by Category	**12.5%**	**19.0%**	**68.6%**	**100.0%**	**100.0%**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), 50% decomp					
Cup + sleeve production	53.7	93.2	0	147	31.6%
End-of-life	0	-9.38	327	318	68.4%
Total	**53.7**	**83.8**	**327**	**465**	
Percent by Category	**11.6%**	**18.0%**	**70.4%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (13.3 g), 0% decomp					
Cup production	42.7	68.5	0	111	32.6%
End-of-life	0	-5.14	235	230	67.4%
Total	**42.7**	**63.3**	**235**	**341**	
Percent by Category	**12.5%**	**18.6%**	**68.9%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), 0% decomp					
Cup + sleeve production	55.6	92.5	0	148	30.9%
End-of-life	0	-6.94	338	331	69.1%
Total	**55.6**	**85.6**	**338**	**479**	
Percent by Category	**11.6%**	**17.9%**	**70.5%**	**100.0%**	**100.0%**
PLA-coated ppbd cup (12.7 g), 0% decomp					
Cup production	40.9	69.1	0	110.0	33.3%
End-of-life	0	-4.14	225	221	66.7%
Total	**40.9**	**65.0**	**225**	**331**	
Percent by Category	**12.4%**	**19.7%**	**68.0%**	**100.0%**	**100.0%**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), 0% decomp					
Cup production	53.7	93.2	0	147	31.4%
End-of-life	0	-5.94	327	321	68.6%
Total	**53.7**	**87.3**	**327**	**468**	
Percent by Category	**11.5%**	**18.6%**	**69.9%**	**100.0%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Table 2-16. Solid Waste by Weight for Average Weight 32-oz Cold Cups
(Pounds per 10,000 cups)

	Process	Fuel	Postconsumer (LF + WTE ash)	Total	Percent by Stage
EPS foam cup (8.8 g)					
Cup production	8.48	59.1	0	67.6	31.3%
End-of-life	0	-7.01	156	149	68.7%
Total	**8.48**	**52.1**	**156**	**216**	
Percent by Category	**3.9%**	**24.1%**	**72.0%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (19.8 g), max decomp					
Cup production	71.5	106	0	177	32.4%
End-of-life	0	-17.8	387	369	67.6%
Total	**71.5**	**87.8**	**387**	**546**	
Percent by Category	**13.1%**	**16.1%**	**70.8%**	**100.0%**	**100.0%**
Wax-coated ppbd cup (31.3 g), max decomp					
Cup production	122	197	0	320	32.2%
End-of-life	0	-32.6	707	674	67.8%
Total	**122**	**165**	**707**	**994**	
Percent by Category	**12.3%**	**16.6%**	**71.1%**	**100.0%**	**100.0%**
Solid PLA cup, based on sample weights (35 g)					
Cup production	2.54	183	0	186	23.6%
End-of-life	0	-12.7	616	603	76.4%
Total	**2.54**	**171**	**616**	**789**	
Percent by Category	**0.3%**	**21.6%**	**78.1%**	**100.0%**	**100.0%**
Solid PLA cup, calculated using resin densities (32.4 g)					
Cup production	2.35	170	0	172	23.6%
End-of-life	0	-11.75	570	558	76.4%
Total	**2.35**	**158**	**570**	**731**	
Percent by Category	**0.3%**	**21.6%**	**78.1%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (19.8 g), 50% decomp					
Cup production	71.5	106	0	177	32.1%
End-of-life	0	-13.0	387	374	67.9%
Total	**71.5**	**92.6**	**387**	**551**	
Percent by Category	**13.0%**	**16.8%**	**70.2%**	**100.0%**	**100.0%**
Wax-coated ppbd cup (31.3 g), 50% decomp					
Cup production	122	197	0	320	31.9%
End-of-life	0	-23.7	707	683	68.1%
Total	**122**	**174**	**707**	**1,003**	
Percent by Category	**12.2%**	**17.3%**	**70.5%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (19.8 g), 0% decomp					
Cup production	71.5	106	0	177	31.9%
End-of-life	0	-8.20	387	379	68.1%
Total	**71.5**	**97.4**	**387**	**556**	
Percent by Category	**12.9%**	**17.5%**	**69.6%**	**100.0%**	**100.0%**
Wax-coated ppbd cup (31.3 g), 0% decomp					
Cup production	132	197	0	330	32.3%
End-of-life	0	-14.8	707	692	67.7%
Total	**132**	**183**	**707**	**1,022**	
Percent by Category	**13.0%**	**17.9%**	**69.2%**	**100.0%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Table 2-17. Solid Waste by Weight for Average Weight Heavy Duty 9-inch Plates
(Pounds per 10,000 plates)

	Process	Fuel	Postconsumer (LF + WTE ash)	Total	Percent by Stage
GPPS foam plate (10.8 g)					
Plate production	10.1	48.5	0	58.7	24.4%
End-of-life	0	-8.57	190	182	75.6%
Total	**10.1**	**40.0**	**190**	**240**	
Percent by Category	**4.2%**	**16.6%**	**79.2%**	**100.0%**	**100.0%**
LDPE-coated plate (18.4 g), max decomp					
Plate production	60.5	99.0	0	160	34.0%
End-of-life	0	-14.9	324	309	66.0%
Total	**60.5**	**84.1**	**324**	**469**	
Percent by Category	**12.9%**	**17.9%**	**69.1%**	**100.0%**	**100.0%**
Molded pulp plate (16.6 g), max decomp					
Plate production	61.5	129	0	191	40.5%
End-of-life	0	-13.4	294	280	59.5%
Total	**61.5**	**116**	**294**	**471**	
Percent by Category	**13.1%**	**24.6%**	**62.3%**	**100.0%**	**100.0%**
Solid PLA plate (20.7 g)					
Plate production	1.50	108.5	0	110.0	23.6%
End-of-life	0	-7.52	365	357	76.4%
Total	**1.50**	**101.0**	**365**	**467**	
Percent by Category	**0.3%**	**21.6%**	**78.1%**	**100.0%**	**100.0%**
LDPE-coated plate (18.4 g), 50% decomp					
Plate production	60.5	99.0	0	160	33.7%
End-of-life	0	-10.8	324	313	66.3%
Total	**60.5**	**88.2**	**324**	**473**	
Percent by Category	**12.8%**	**18.7%**	**68.5%**	**100.0%**	**100.0%**
Molded pulp plate (16.6 g), 50% decomp					
Plate production	61.5	129	0	191	40.2%
End-of-life	0	-9.38	294	284	59.8%
Total	**61.5**	**120**	**294**	**475**	
Percent by Category	**12.9%**	**25.3%**	**61.8%**	**100.0%**	**100.0%**
LDPE-coated plate (18.4 g), 0% decomp					
Plate production	60.5	99.0	0	160	33.5%
End-of-life	0	-6.73	324	317	66.5%
Total	**60.5**	**92.3**	**324**	**477**	
Percent by Category	**12.7%**	**19.4%**	**68.0%**	**100.0%**	**100.0%**
Molded pulp plate (16.6 g), 0% decomp					
Plate production	61.5	129	0	191	39.8%
End-of-life	0	-5.36	294	288	60.2%
Total	**61.5**	**124**	**294**	**479**	
Percent by Category	**12.8%**	**25.9%**	**61.3%**	**100.0%**	**100.0%**
LIGHT-WEIGHT PLATES					
2009 GPPS Foam Plate (4.7 g)					
Plate production	4.41	21.1	0	25.5	24.4%
End-of-life	0	-3.73	82.8	79.1	75.6%
Total	**4.41**	**17.4**	**82.8**	**105**	
Percent by Category	**4.2%**	**16.6%**	**79.2%**	**100.0%**	**100.0%**
2009 LDPE-coated plate (12.1 g), equiv strength, max decomp					
Plate production	39.9	65.3	0	105	34.0%
End-of-life	0	-9.83	214	204	66.0%
Total	**39.9**	**55.5**	**214**	**309**	
Percent by Category	**12.9%**	**17.9%**	**69.1%**	**100.0%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Table 2-18. Solid Waste by Weight for Average Weight Sandwich-size Clamshells
(Pounds per 10,000 clamshells)

	Process	Fuel	Postconsumer (LF + WTE ash)	Total	Percent by Stage
GPPS foam clamshell (4.8 g)					
Clamshell production	4.52	26.2	0	30.7	27.5%
End-of-life	0	-3.81	84.6	80.8	72.5%
Total	**4.52**	**22.4**	**84.6**	**111**	
Percent by Category	**4.1%**	**20.1%**	**75.9%**	**100.0%**	**100.0%**
Fluted paperboard clamshell (10.2 g), max decomp					
Clamshell production	22.5	64.4	0	86.9	33.1%
End-of-life	0	-6.39	182	175	66.9%
Total	**22.5**	**58.0**	**182**	**262**	
Percent by Category	**8.6%**	**22.1%**	**69.3%**	**100.0%**	**100.0%**
Solid PLA clamshell (23.3 g)					
Clamshell production	1.69	162	0	164	29.0%
End-of-life	0	-8.46	411	402	71.0%
Total	**1.69**	**154**	**411**	**566**	
Percent by Category	**0.3%**	**27.2%**	**72.5%**	**100.0%**	**100.0%**
Fluted paperboard clamshell (10.2 g), 50% decomp					
Clamshell production	22.5	64.4	0	86.9	32.9%
End-of-life	0	-4.81	182	177	67.1%
Total	**22.5**	**59.6**	**182**	**264**	
Percent by Category	**8.5%**	**22.6%**	**68.9%**	**100.0%**	**100.0%**
Fluted paperboard clamshell (10.2 g), 0% decomp					
Clamshell production	22.5	64.4	0	86.9	32.7%
End-of-life	0	-3.23	182	179	67.3%
Total	**22.5**	**61.2**	**182**	**266**	
Percent by Category	**8.5%**	**23.0%**	**68.5%**	**100.0%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Figure 2-5. Weight of Solid Waste for 16-oz Hot Cups (10,000 average weight cups)

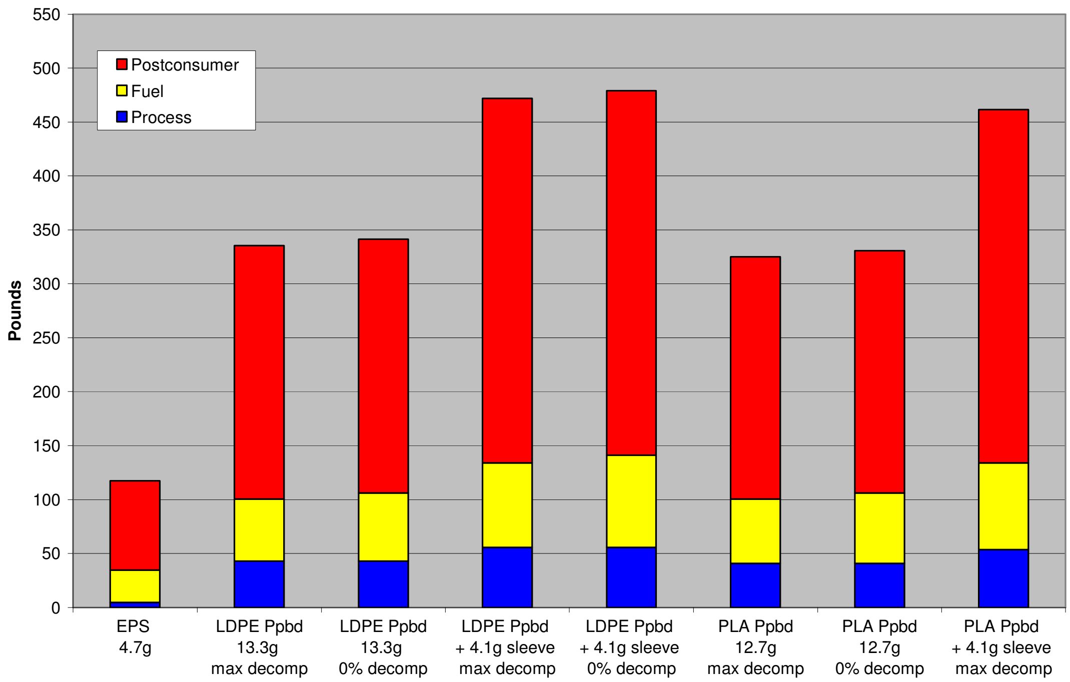


Figure 2-6. Weight of Solid Waste for 32-oz Cold Cups (10,000 average weight cups)

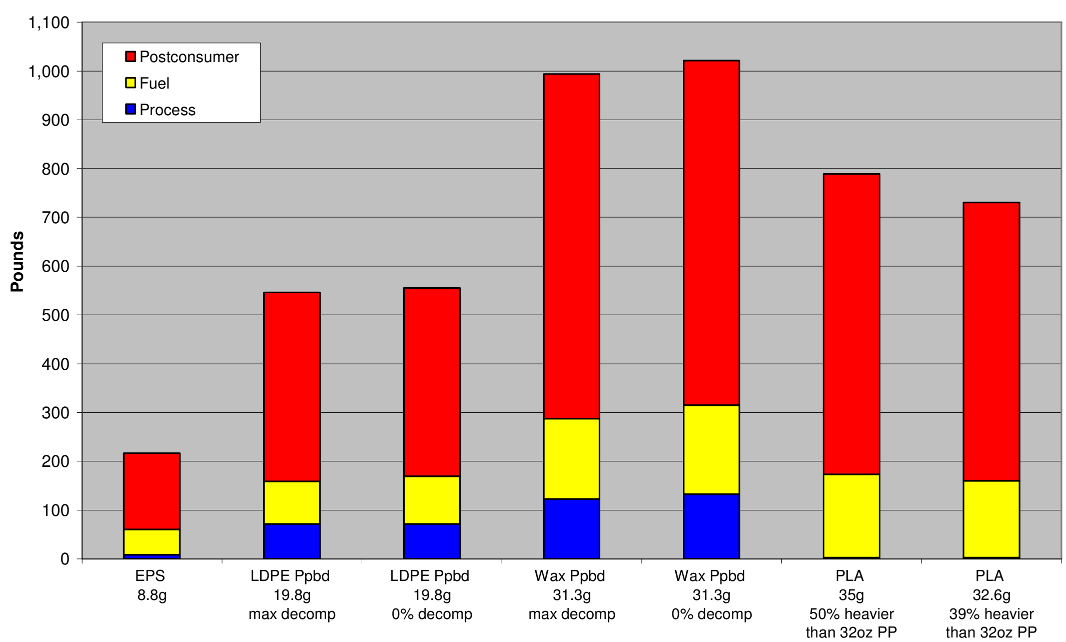


Figure 2-7. Weight of Solid Waste for 9-inch Plates (10,000 average weight plates)

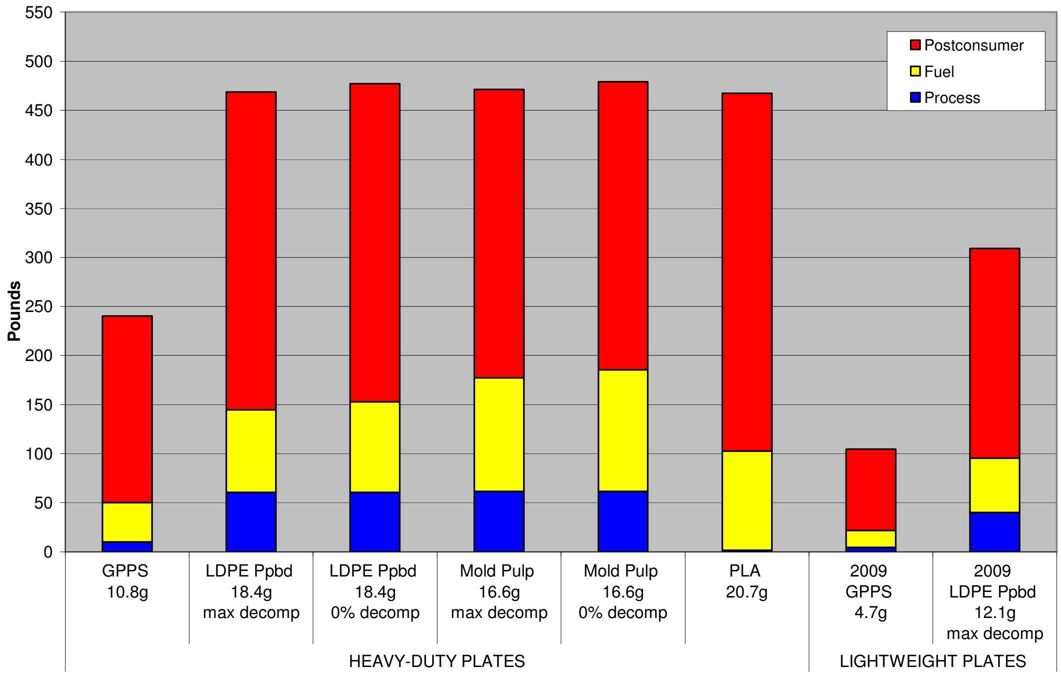
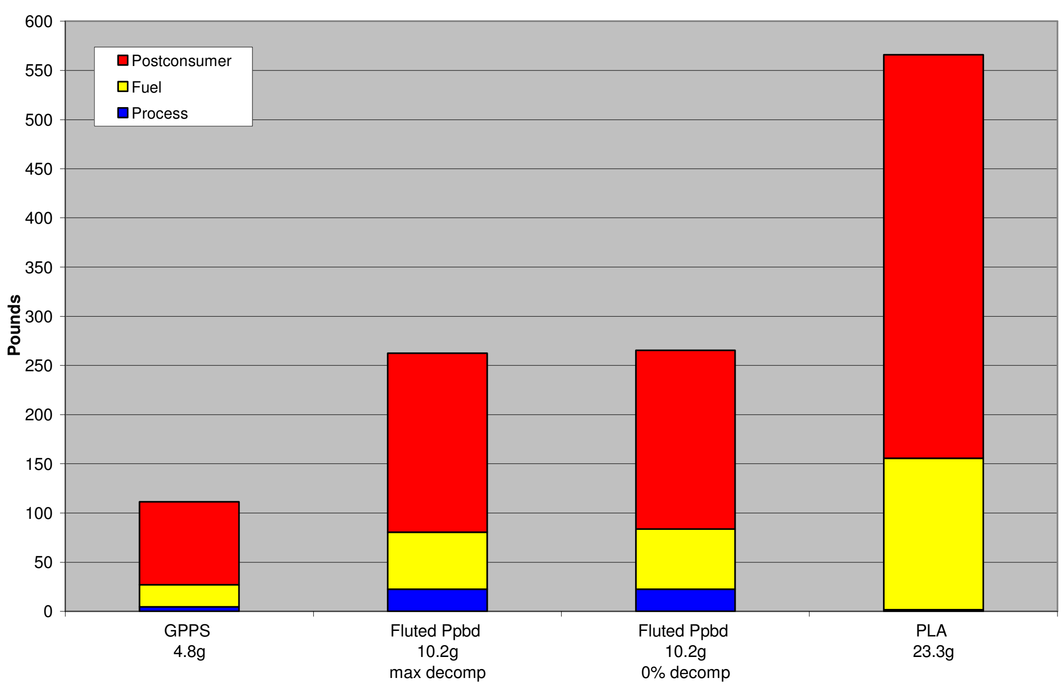


Figure 2-8. Weight of Solid Waste for Sandwich-size Clamshells (10,000 average weight clamshells)



Volume of Solid Waste. Results for solid waste by volume are shown in Tables 2-19 through 2-22 and Figures 2-9 through 2-12. Weights of process- and fuel-related wastes are converted to volume using an average density factor of 50 pounds per cubic foot (1,350 pounds per cubic yard). The weights of postconsumer products are converted to volume using density factors that take into account not only the density of each material but also the degree to which these materials compact in the landfill. The landfill densities used for the conversions are shown in Table 2-23.

The lower the landfill density, the more space the postconsumer materials take up. Foam products have a lower landfill density than paperboard or solid PLA products, so each pound of foam product takes up more landfill space than a pound of paperboard or PLA product. Comparing the postconsumer solid waste segments in the solid waste weight and volume figures shows how the lower landfill density of foam foodservice products results in a volume of postconsumer solid waste that is similar to (and in some cases, higher than) the volume of paperboard and solid PLA products.

Table 2-19. Solid Waste by Volume for Average Weight 16-oz Hot Cups
(Cubic Feet per 10,000 cups)

	Process	Fuel	Postconsumer (LF + WTE ash)	Total	Percent by Stage
EPS foam cup (4.7 g)					
Cup production	0.092	0.67	0	0.76	7.6%
End-of-life	0	-0.075	9.32	9.24	92.4%
Total	**0.092**	**0.60**	**9.32**	**10.0**	
Percent by Category	**0.9%**	**6.0%**	**93.1%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (13.3 g), max decomp					
Cup production	0.85	1.37	0	2.22	20.8%
End-of-life	0	-0.22	8.68	8.46	79.2%
Total	**0.85**	**1.15**	**8.68**	**10.7**	
Percent by Category	**8.0%**	**10.8%**	**81.2%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), max decomp					
Cup + sleeve production	1.11	1.85	0	2.96	19.7%
End-of-life	0	-0.28	12.4	12.1	80.3%
Total	**1.11**	**1.57**	**12.4**	**15.0**	
Percent by Category	**7.4%**	**10.5%**	**82.2%**	**100.0%**	**100.0%**
PLA-coated ppbd cup (12.7 g), max decomp					
Cup production	0.82	1.38	0	2.20	21.4%
End-of-life	0	-0.20	8.27	8.07	78.6%
Total	**0.82**	**1.19**	**8.27**	**10.3**	
Percent by Category	**8.0%**	**11.6%**	**80.5%**	**100.0%**	**100.0%**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), max decomp					
Cup + sleeve production	1.07	1.86	0	2.94	20.1%
End-of-life	0	-0.26	11.9	11.7	79.9%
Total	**1.07**	**1.61**	**11.9**	**14.6**	
Percent by Category	**7.3%**	**11.0%**	**81.7%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (13.3 g), 50% decomp					
Cup production	0.85	1.37	0	2.22	20.7%
End-of-life	0	-0.16	8.68	8.52	79.3%
Total	**0.85**	**1.21**	**8.68**	**10.7**	
Percent by Category	**8.0%**	**11.3%**	**80.8%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), 50% decomp					
Cup + sleeve production	1.11	1.85	0	2.96	19.6%
End-of-life	0	-0.21	12.4	12.1	80.4%
Total	**1.11**	**1.64**	**12.4**	**15.1**	
Percent by Category	**7.4%**	**10.9%**	**81.8%**	**100.0%**	**100.0%**
PLA-coated ppbd cup (12.7 g), 50% decomp					
Cup production	0.82	1.38	0	2.20	21.3%
End-of-life	0	-0.14	8.27	8.13	78.7%
Total	**0.82**	**1.24**	**8.27**	**10.3**	
Percent by Category	**7.9%**	**12.0%**	**80.0%**	**100.0%**	**100.0%**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), 50% decomp					
Cup + sleeve production	1.07	1.86	0	2.94	20.0%
End-of-life	0	-0.19	11.9	11.8	80.0%
Total	**1.07**	**1.68**	**11.9**	**14.7**	
Percent by Category	**7.3%**	**11.4%**	**81.3%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (13.3 g), 0% decomp					
Cup production	0.85	1.37	0	2.22	20.6%
End-of-life	0	-0.10	8.68	8.57	79.4%
Total	**0.85**	**1.27**	**8.68**	**10.8**	
Percent by Category	**7.9%**	**11.7%**	**80.4%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), 0% decomp					
Cup + sleeve production	1.11	1.85	0	2.96	19.5%
End-of-life	0	-0.14	12.4	12.2	80.5%
Total	**1.11**	**1.71**	**12.4**	**15.2**	
Percent by Category	**7.3%**	**11.3%**	**81.4%**	**100.0%**	**100.0%**
PLA-coated ppbd cup (12.7 g), 0% decomp					
Cup production	0.82	1.38	0	2.20	21.2%
End-of-life	0	-0.083	8.27	8.18	78.8%
Total	**0.82**	**1.30**	**8.27**	**10.4**	
Percent by Category	**7.9%**	**12.5%**	**79.6%**	**100.0%**	**100.0%**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), 0% decomp					
Cup production	1.07	1.86	0	2.94	19.9%
End-of-life	0	-0.12	11.9	11.8	80.1%
Total	**1.07**	**1.75**	**11.9**	**14.8**	
Percent by Category	**7.3%**	**11.8%**	**80.9%**	**100.0%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Table 2-20. Solid Waste by Volume for Average Weight 32-oz Cold Cups
(Cubic Feet per 10,000 cups)

	Process	Fuel	Postconsumer (LF + WTE ash)	Total	Percent by Stage
EPS foam cup (8.8 g)					
Cup production	0.17	1.18	0	1.35	7.2%
End-of-life	0	-0.14	17.5	17.4	92.8%
Total	**0.17**	**1.04**	**17.5**	**18.7**	
Percent by Category	**0.9%**	**5.6%**	**93.5%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (19.8 g), max decomp					
Cup production	1.43	2.11	0	3.54	20.3%
End-of-life	0	-0.36	14.2	13.9	79.7%
Total	**1.43**	**1.76**	**14.2**	**17.4**	
Percent by Category	**8.2%**	**10.1%**	**81.7%**	**100.0%**	**100.0%**
Wax-coated ppbd cup (31.3 g), max decomp					
Cup production	2.65	3.95	0	6.60	20.7%
End-of-life	0	-0.65	26.0	25.3	79.3%
Total	**2.65**	**3.30**	**26.0**	**31.9**	
Percent by Category	**8.3%**	**10.3%**	**81.4%**	**100.0%**	**100.0%**
Solid PLA cup, based on sample weights (35 g)					
Cup production	0.05	3.67	0	3.72	13.1%
End-of-life	0	-0.25	24.9	24.7	86.9%
Total	**0.05**	**3.41**	**24.9**	**28.4**	
Percent by Category	**0.2%**	**12.0%**	**87.8%**	**100.0%**	**100.0%**
Solid PLA cup, calculated using resin densities (32.4 g)					
Cup production	0.047	3.39	0	3.44	13.1%
End-of-life	0	-0.24	23.1	22.8	86.9%
Total	**0.047**	**3.16**	**23.1**	**26.3**	
Percent by Category	**0.2%**	**12.0%**	**87.8%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (19.8 g), 50% decomp					
Cup production	1.43	2.11	0	3.54	20.2%
End-of-life	0	-0.26	14.2	14.0	79.8%
Total	**1.43**	**1.85**	**14.2**	**17.5**	
Percent by Category	**8.2%**	**10.6%**	**81.3%**	**100.0%**	**100.0%**
Wax-coated ppbd cup (31.3 g), 50% decomp					
Cup production	2.65	3.95	0	6.60	20.6%
End-of-life	0	-0.47	26.0	25.5	79.4%
Total	**2.65**	**3.48**	**26.0**	**32.1**	
Percent by Category	**8.3%**	**10.8%**	**80.9%**	**100.0%**	**100.0%**
LDPE-coated ppbd cup (19.8 g), 0% decomp					
Cup production	1.43	2.11	0	3.54	20.1%
End-of-life	0	-0.16	14.2	14.1	79.9%
Total	**1.43**	**1.95**	**14.2**	**17.6**	
Percent by Category	**8.1%**	**11.1%**	**80.8%**	**100.0%**	**100.0%**
Wax-coated ppbd cup (31.3 g), 0% decomp					
Cup production	2.65	3.95	0	6.60	20.4%
End-of-life	0	-0.30	26.0	25.7	79.6%
Total	**2.65**	**3.65**	**26.0**	**32.3**	
Percent by Category	**8.2%**	**11.3%**	**80.5%**	**100.0%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Table 2-21. Solid Waste by Volume for Average Weight Heavy Duty 9-inch Plates
(Cubic Feet per 10,000 plates)

	Process	Fuel	Postconsumer (LF + WTE ash)	Total	Percent by Stage
GPPS foam plate (10.8 g)					
Plate production	0.20	0.97	0	1.17	5.2%
End-of-life	0	-0.17	21.4	21.2	94.8%
Total	**0.20**	**0.80**	**21.4**	**22.4**	
Percent by Category	**0.9%**	**3.6%**	**95.5%**	**100.0%**	**100.0%**
LDPE-coated plate (18.4 g), max decomp					
Plate production	1.21	1.98	0	3.19	21.6%
End-of-life	0	-0.30	11.9	11.6	78.4%
Total	**1.21**	**1.68**	**11.9**	**14.8**	
Percent by Category	**8.2%**	**11.4%**	**80.5%**	**100.0%**	**100.0%**
Molded pulp plate (16.6 g), max decomp					
Plate production	1.23	2.59	0	3.82	26.8%
End-of-life	0	-0.27	10.7	10.4	73.2%
Total	**1.23**	**2.32**	**10.7**	**14.3**	
Percent by Category	**8.6%**	**16.3%**	**75.1%**	**100.0%**	**100.0%**
Solid PLA plate (20.7 g)					
Plate production	0.030	2.17	0	2.20	13.1%
End-of-life	0	-0.15	14.8	14.6	86.9%
Total	**0.030**	**2.02**	**14.8**	**16.8**	
Percent by Category	**0.2%**	**12.0%**	**87.8%**	**100.0%**	**100.0%**
LDPE-coated plate (18.4 g), 50% decomp					
Plate production	1.21	1.98	0	3.19	21.4%
End-of-life	0	-0.22	11.9	11.7	78.6%
Total	**1.21**	**1.76**	**11.9**	**14.9**	
Percent by Category	**8.1%**	**11.9%**	**80.0%**	**100.0%**	**100.0%**
Molded pulp plate (16.6 g), 50% decomp					
Plate production	1.23	2.59	0	3.82	26.6%
End-of-life	0	-0.19	10.7	10.5	73.4%
Total	**1.23**	**2.40**	**10.7**	**14.3**	
Percent by Category	**8.6%**	**16.7%**	**74.7%**	**100.0%**	**100.0%**
LDPE-coated plate (18.4 g), 0% decomp					
Plate production	1.21	1.98	0	3.19	21.3%
End-of-life	0	-0.13	11.9	11.8	78.7%
Total	**1.21**	**1.85**	**11.9**	**15.0**	
Percent by Category	**8.1%**	**12.3%**	**79.6%**	**100.0%**	**100.0%**
Molded pulp plate (16.6 g), 0% decomp					
Plate production	1.23	2.59	0	3.82	26.5%
End-of-life	0	-0.11	10.7	10.6	73.5%
Total	**1.23**	**2.48**	**10.7**	**14.4**	
Percent by Category	**8.5%**	**17.2%**	**74.3%**	**100.0%**	**100.0%**
LIGHT-WEIGHT PLATES					
2009 GPPS Foam Plate (4.7 g)					
Plate production	0.088	0.42	0	0.51	5.2%
End-of-life	0	-0.075	9.32	9.24	94.8%
Total	**0.088**	**0.35**	**9.32**	**9.75**	
Percent by Category	**0.9%**	**3.6%**	**95.5%**	**100.0%**	**100.0%**
2009 LDPE-coated plate (12.1 g), equiv strength, max decomp					
Plate production	0.80	1.31	0	2.10	21.6%
End-of-life	0	-0.20	7.86	7.66	78.4%
Total	**0.80**	**1.11**	**7.86**	**9.76**	
Percent by Category	**8.2%**	**11.4%**	**80.5%**	**100.0%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Table 2-22. Solid Waste by Volume for Average Weight Sandwich-size Clamshells
(Cubic Feet per 10,000 clamshells)

	Process	Fuel	Postconsumer (LF + WTE ash)	Total	Percent by Stage
GPPS foam clamshell (4.8 g)					
Clamshell production	0.090	0.52	0	0.61	6.1%
End-of-life	0	-0.076	9.52	9.44	93.9%
Total	**0.090**	**0.45**	**9.52**	**10.1**	
Percent by Category	**0.9%**	**4.5%**	**94.7%**	**100.0%**	**100.0%**
Fluted paperboard clamshell (10.2 g), max decomp					
Clamshell production	0.45	1.29	0	1.74	21.3%
End-of-life	0	-0.13	6.55	6.42	78.7%
Total	**0.45**	**1.16**	**6.55**	**8.16**	
Percent by Category	**5.5%**	**14.2%**	**80.3%**	**100.0%**	**100.0%**
Solid PLA clamshell (23.3 g)					
Clamshell production	0.034	3.25	0	3.28	16.6%
End-of-life	0	-0.17	16.6	16.5	83.4%
Total	**0.034**	**3.08**	**16.6**	**19.7**	
Percent by Category	**0.2%**	**15.6%**	**84.2%**	**100.0%**	**100.0%**
Fluted paperboard clamshell (10.2 g), 50% decomp					
Clamshell production	0.45	1.29	0	1.74	21.2%
End-of-life	0	-0.096	6.55	6.45	78.8%
Total	**0.45**	**1.19**	**6.55**	**8.19**	
Percent by Category	**5.5%**	**14.6%**	**80.0%**	**100.0%**	**100.0%**
Fluted paperboard clamshell (10.2 g), 0% decomp					
Clamshell production	0.45	1.29	0	1.74	21.1%
End-of-life	0	-0.065	6.55	6.48	78.9%
Total	**0.45**	**1.22**	**6.55**	**8.22**	
Percent by Category	**5.5%**	**14.9%**	**79.6%**	**100.0%**	**100.0%**

Source: Franklin Associates, A Division of ERG

Figure 2-9. Volume of Solid Waste for 16-oz Hot Cups (10,000 average weight cups)

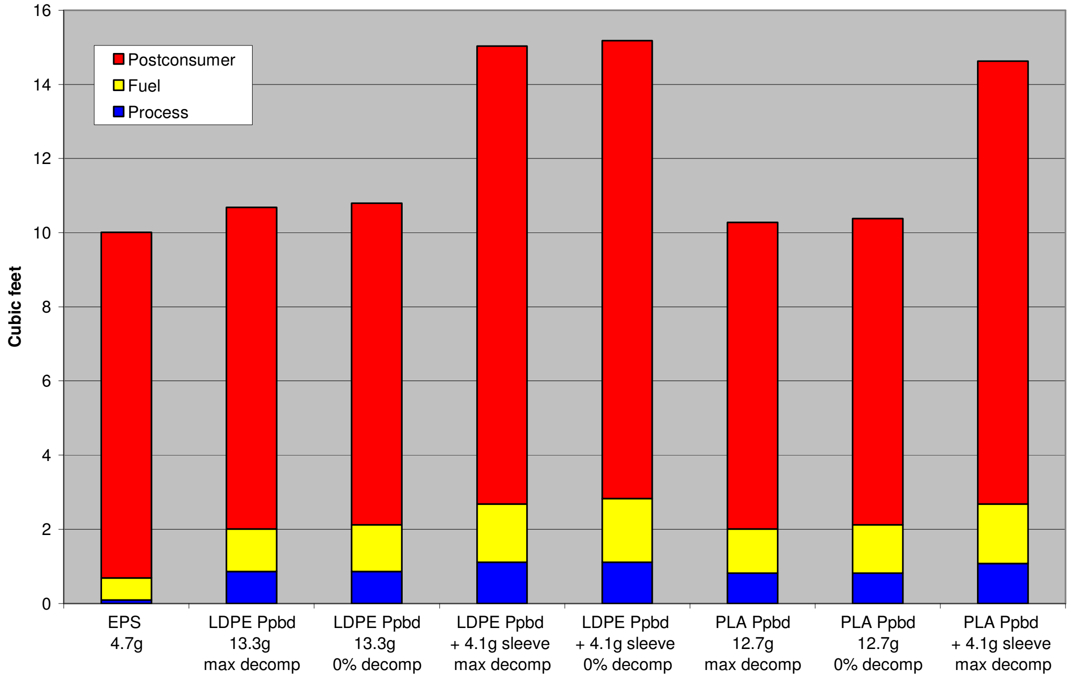


Figure 2-10. Volume of Solid Waste for 32-oz Cold Cups (10,000 average weight cups)

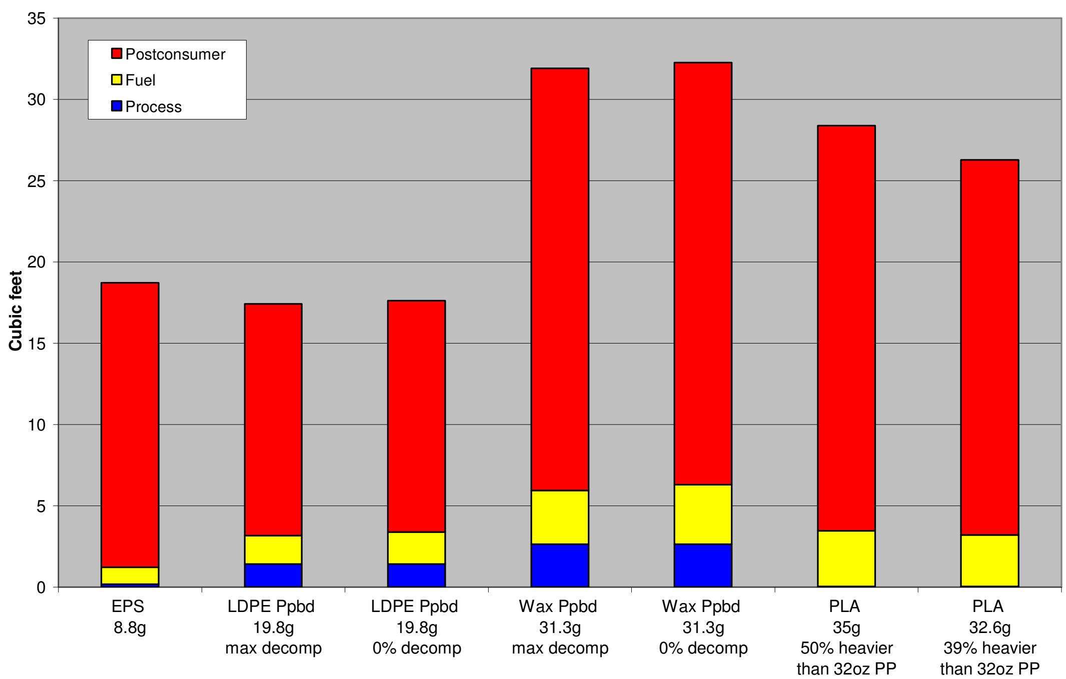


Figure 2-11. Volume of Solid Waste for 9-inch Plates
(10,000 average weight plates)

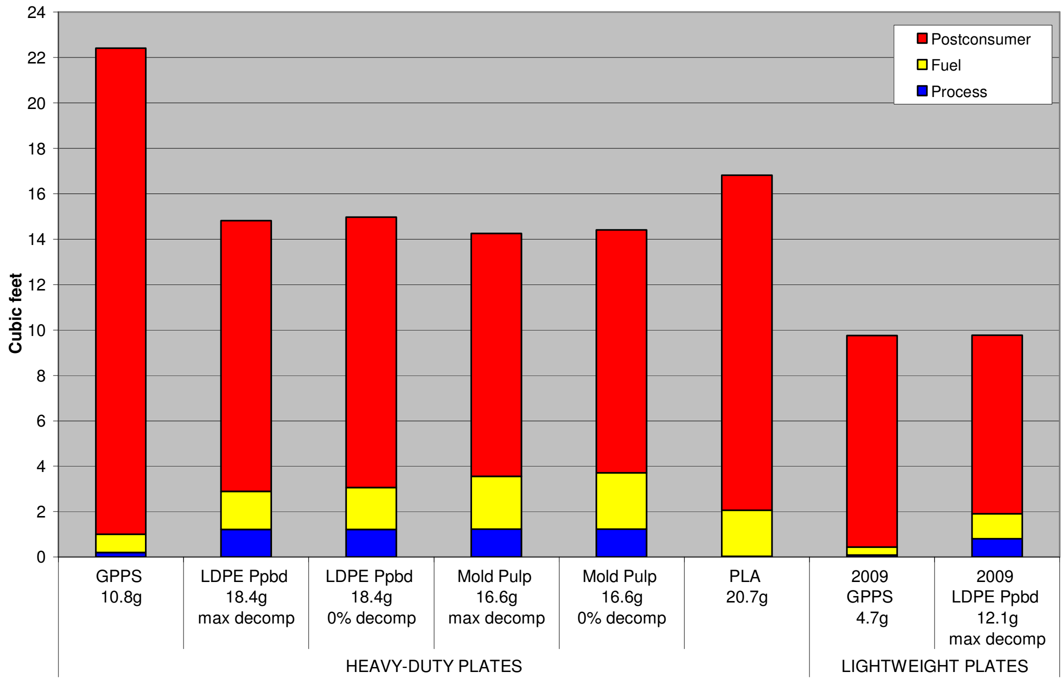


Figure 2-12. Volume of Solid Waste for Sandwich-size Clamshells
(10,000 average weight clamshells)

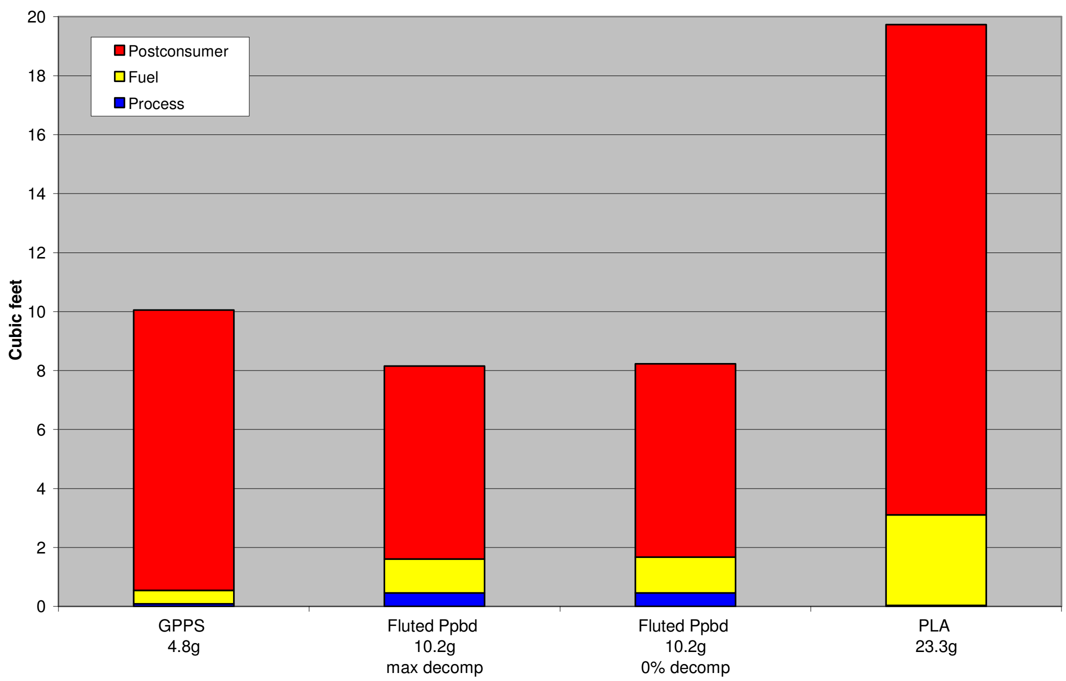


Table 2-23. LANDFILL DENSITIES FOR FOODSERVICE PRODUCTS

	Landfill Density (lb/cu yd)
EPS foam items	240 (1)
GPPS foam items	240 (1)
Coated paperboard cups	740 (2), (3)
Molded fiber and coated paperboard plates	740 (2), (3)
Solid (non-foam) plastic cups and clamshells	355 (2), (4)
Solid (non-foam) plastic plates	667 (2), (4)
Corrugated sleeves and clamshells	750 (2)
Industrial wastes (process wastes, fuel-related wastes, WTE ash)	1350 (5)

Sources:

(1) Landfill simulation experiments on polystyrene foam foodservice products conducted for a confidential client by The Garbage Project in 1995.

(2) **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. The report contains no data specifically for foodservice products, so the densities used to represent plates in this analysis were based on products that would compact similarly.

(3) The density for paper packaging was used to represent non-corrugated paper foodservice items.

(4) The density options in the report for plastic products were plastic film and rigid containers. The density for rigid plastic containers was used to represent solid plastic cups and clamshells. The density for plastic film was used to represent solid plastic plates, since flat plates would compact more densely than other rigid plastic containers.

(5) **Characterization of Municipal Solid Waste in the United States: 1997 Update.** EPA 530-R-98-007. May 1998. Conducted for the U.S. EPA Municipal and Industrial Solid Waste Division, Office of Solid Waste, by Franklin Associates.

Environmental Emissions

The emissions reported in this analysis include those associated with production of materials and production and combustion of fuels and are based upon the best data available. However, in the many unit processes included in the system models, some emissions data have been reported from industrial sources, some are estimated from EPA emission factors, and some have been calculated based on reaction chemistry or other information. This means there are significant uncertainties with regards to the application of the data to these particular product systems. Because of these uncertainties, the difference in two systems' emissions of a given substance is 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.

Atmospheric and waterborne emissions for each system include emissions from processes and emissions associated with the combustion of fuels. **Process emissions** are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise effect changes on a material or product during its life cycle, while **fuel-related emissions** are those associated with the combustion of fuels used for process energy and transportation energy. The majority of atmospheric emissions are fuel-related, particularly in the case of greenhouse gas emissions, which are the focus of this discussion.

Greenhouse Gas Results. In this analysis, results for greenhouse gas emissions are reported in terms of carbon dioxide equivalents (CO_2 eq). Each greenhouse gas has a global warming potential (GWP) that represents its global warming contribution relative to an equivalent quantity of carbon dioxide. As defined in the International Panel on Climate Change (IPCC) Second Assessment Report (SAR), published in 1996, GWPs are calculated as the ratio of the radiative forcing that would result from the emissions of one kilogram of a greenhouse gas to that from emission of one kilogram of carbon dioxide over a period of time (usually 100 years). Radiative forcing is a measure of how the energy balance of the Earth-atmosphere system is influenced when factors that affect climate are altered.

The weight of releases of each greenhouse gas is multiplied by its GWP, then results for all GHGs are added to arrive at the total CO_2 eq. All CO_2 calculations, including CO_2 eq calculations for the aggregated methane releases from decomposition of landfilled paper products, are based on 100-year GWP factors.

The primary three atmospheric emissions reported in this analysis that contribute over 99.9 percent of the total CO_2 eq for each system are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.)

The GWP factors that are most widely used are those from the IPCC 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.[32] The IPCC SAR 100-year global warming potentials (GWP) are 21 for methane and 310 for nitrous oxide.

In addition to process and fuel-related greenhouse gas emissions, Tables 2-23 through 2-26 also include estimates of CO_2 eq associated with end-of-life management of postconsumer foodservice items. The methodology and data sources used to estimate CO_2 eq from WTE combustion of postconsumer products, CO_2 eq from landfill gas emissions, CO_2 eq credits for displacement of grid electricity, and carbon sequestration credits are described in detail in the End of Life Management section of Chapter 1.

[32] 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-3 of EPA 430-R-10-006 **Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008** (April 2010). The U.S. EPA Mandatory Greenhouse Gas Reporting Rule, published in the Federal Register / Vol. 74, No. 209 / Friday, October 30, 2009 / Rules and Regulations, also uses 100-year GWPs from the SAR (http://www.epa.gov/climatechange/emissions/downloads09/GHG-MRR-FinalRule.pdf; GWP factors are in Table A-1 on p. 56395 of Part 98).

Table 2-24. Greenhouse Gas Emissions for Average Weight 16-oz Hot Cups
(Pounds of CO2 Equivalents per 10,000 cups)

	Process	Fuel	WTE combustion emissions	Displaced kWh credit	LF methane	C02 equiv for C seq	Net CO2 eq
EPS foam cup (4.7 g)							
Cup production	58.0	622	0	0	0	0	680
End-of-life	0	6.82	70.1	-33.2	0	0	43.7
Total	**58.0**	**628**	**70.1**	**-33.2**	**0**	**0**	**723**
LDPE-coated ppbd cup (13.3 g), max decomp							
Cup production	20.4	482	0	0	0	0	502
End-of-life	0	7.35	20.5	-95.0	573	-21.3	485
Total	**20.4**	**489**	**20.5**	**-95.0**	**573**	**-21.3**	**987**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), max decomp							
Cup + sleeve production	21.3	694	0	0	0	0	715
End-of-life	0	10.5	20.5	-122	702	-111	500
Total	**21.3**	**705**	**20.5**	**-122**	**702**	**-111**	**1,215**
PLA-coated ppbd cup (12.7 g), max decomp							
Cup production	20.0	468	0	0	0	0	488
End-of-life	0	7.02	0	-85.4	562	-56.6	427
Total	**20.0**	**475**	**0**	**-85.4**	**562**	**-56.6**	**916**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), max decomp							
Cup + sleeve production	20.9	681	0	0	0	0	702
End-of-life	0	10.2	0	-112	691	-146	442
Total	**20.9**	**691**	**0**	**-112**	**691**	**-146**	**1144**
LDPE-coated ppbd cup (13.3 g), 50% decomp							
Cup production	20.4	482	0	0	0	0	502
End-of-life	0	7.35	20.5	-70.3	287	-179	64.8
Total	**20.4**	**489**	**20.5**	**-70.3**	**287**	**-179**	**567**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), 50% decomp							
Cup + sleeve production	21.3	694	0	0	0	0	715
End-of-life	0	10.5	20.5	-91.8	351	-305	-14.6
Total	**21.3**	**705**	**20.5**	**-91.8**	**351**	**-305**	**701**
PLA-coated ppbd cup (12.7 g), 50% decomp							
Cup production	20.0	468	0	0	0	0	488
End-of-life	0	7.02	0	-61.1	281	-212	15.4
Total	**20.0**	**475**	**0**	**-61.1**	**281**	**-212**	**504**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), 50% decomp							
Cup + sleeve production	20.9	681	0	0	0	0	702
End-of-life	0	10.2	0	-82.6	346	-337	-64.0
Total	**20.9**	**691**	**0**	**-82.6**	**346**	**-337**	**638**
LDPE-coated ppbd cup (13.3 g), 0% decomp							
Cup production	20.4	482	0	0	0	0	502
End-of-life	0	7.35	20.5	-45.5	0	-338	-355
Total	**20.4**	**489**	**20.5**	**-45.5**	**0**	**-338**	**147**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), 0% decomp							
Cup + sleeve production	21.3	694	0	0	0	0	715
End-of-life	0	10.5	20.5	-61.5	0	-498	-529
Total	**21.3**	**705**	**20.5**	**-61.5**	**0**	**-498**	**186**
PLA-coated ppbd cup (12.7 g), 0% decomp							
Cup production	20.0	468	0	0	0	0	488
End-of-life	0	7.02	0	-36.8	0	-367	-397
Total	**20.0**	**475**	**0**	**-36.8**	**0**	**-367**	**91.6**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), 0% decomp							
Cup production	20.9	681	0	0	0	0	702
End-of-life	0	10.2	0	-52.7	0	-528	-570
Total	**20.9**	**691**	**0**	**-52.7**	**0**	**-528**	**131**

Source: Franklin Associates, A Division of ERG

Table 2-25. Greenhouse Gas Emissions for Average Weight 32-oz Cold Cups
(Pounds of CO2 Equivalents per 10,000 cups)

	Process	Fuel	WTE combustion emissions	Displaced kWh credit	LF methane	C02 equiv for C seq	Net CO2 eq
EPS foam cup (8.8 g)							
Cup production	107	1,120	0	0	0	0	1,227
End-of-life	0	12.8	132	-62.3	0	0	82.2
Total	**107**	**1,133**	**132**	**-62.3**	**0**	**0**	**1,309**
LDPE-coated ppbd cup (19.8 g), max decomp							
Cup production	30.0	713	0	0	0	0	743
End-of-life	0	12.1	27.6	-156	964	-35.7	812
Total	**30.0**	**725**	**27.6**	**-156**	**964**	**-35.7**	**1,555**
Wax-coated ppbd cup (31.3 g), max decomp							
Cup production	31.0	1,275	0	0	0	0	1,306
End-of-life	0	17.3	43.3	-284	1,786	-66.2	1,496
Total	**31.0**	**1,292**	**43.3**	**-284**	**1,786**	**-66.2**	**2,802**
Solid PLA cup, based on sample weights (35 g)							
Cup production	392	2,249	0	0	0	0	2,641
End-of-life	0	19.3	0	-112	0	-1,129	-1,222
Total	**392**	**2,269**	**0**	**-112**	**0**	**-1,129**	**1419**
Solid PLA cup, calculated using resin densities (32.4 g)							
Cup production	101	2344	0	0	0	0	2,446
End-of-life	0	17.9	0	-104.1	0	-1045	-1132
Total	**101**	**2,362**	**0**	**-104.1**	**0**	**-1045**	**1314**
LDPE-coated ppbd cup (19.8 g), 50% decomp							
Cup production	30.0	713	0	0	0	0	743
End-of-life	0	12.1	27.6	-114	482	-302	106
Total	**30.0**	**725**	**27.6**	**-114**	**482**	**-302**	**849**
Wax-coated ppbd cup (31.3 g), 50% decomp							
Cup production	31.0	1,275	0	0	0	0	1,306
End-of-life	0	17.3	43.3	-207	893	-559	187
Total	**31.0**	**1,292**	**43.3**	**-207**	**893**	**-559**	**1,493**
LDPE-coated ppbd cup (19.8 g), 0% decomp							
Cup production	30.0	713	0	0	0	0	743
End-of-life	0	12.1	27.6	-72.6	0	-568	-601
Total	**30.0**	**725**	**27.6**	**-72.6**	**0**	**-568**	**143**
Wax-coated ppbd cup (31.3 g), 0% decomp							
Cup production	31.0	1,275	0	0	0	0	1,306
End-of-life	0	17.3	43.3	-130	0	-1,051	-1,121
Total	**31.0**	**1,292**	**43.3**	**-130**	**0**	**-1,051**	**185**

Source: Franklin Associates, A Division of ERG

Table 2-26. Greenhouse Gas Emissions for Average Weight Heavy Duty 9-inch Plates
(Pounds of CO2 Equivalents per 10,000 plates)

	Process	Fuel	WTE combustion emissions	Displaced kWh credit	LF methane	C02 equiv for C seq	Net CO2 eq
GPPS foam plate (10.8 g)							
Plate production	122	919	0	0	0	0	1,041
End-of-life	0	15.7	161	-76.2	0	0	100
Total	**122**	**935**	**161**	**-76.2**	**0**	**0**	**1,142**
LDPE-coated plate (18.4 g), max decomp							
Plate production	23.3	695	0	0	0	0	718
End-of-life	0	10.1	19.8	-130	819	-30.4	688
Total	**23.3**	**705**	**19.8**	**-130**	**819**	**-30.4**	**1,406**
Molded pulp plate (16.6 g), max decomp							
Plate production	11.4	1,034	0	0	0	0	1,046
End-of-life	0	8.31	0	-117	805	-29.9	666
Total	**11.4**	**1,043**	**0**	**-117**	**805**	**-29.9**	**1,712**
Solid PLA plate (20.7 g)							
Plate production	232	1332	0	0	0	0	1564
End-of-life	0	11.4	0	-66.6	0	-669	-724
Total	**232**	**1343**	**0**	**-66.6**	**0**	**-669**	**840**
LDPE-coated plate (18.4 g), 50% decomp							
Plate production	23.3	695	0	0	0	0	718
End-of-life	0	10.1	19.8	-95.1	410	-256	88.1
Total	**23.3**	**705**	**19.8**	**-95.1**	**410**	**-256**	**806**
Molded pulp plate (16.6 g), 50% decomp							
Plate production	11.4	1,034	0	0	0	0	1,046
End-of-life	0	8.31	0	-82.3	403	-252	76.6
Total	**11.4**	**1,043**	**0**	**-82.3**	**403**	**-252**	**1,122**
LDPE-coated plate (18.4 g), 0% decomp							
Plate production	23.3	695	0	0	0	0	718
End-of-life	0	10.1	19.8	-59.6	0	-482	-512
Total	**23.3**	**705**	**19.8**	**-59.6**	**0**	**-482**	**206**
Molded pulp plate (16.6 g), 0% decomp							
Plate production	11.4	1,034	0	0	0	0	1,046
End-of-life	0	8.31	0	-47.5	0	-474	-513
Total	**11.4**	**1,043**	**0**	**-47.5**	**0**	**-474**	**532**
LIGHT-WEIGHT PLATES							
2009 GPPS Foam Plate (4.7 g)							
Plate production	53.3	400	0	0	0	0	453
End-of-life	0	6.82	70.1	-33.2	0	0	43.7
Total	**53.3**	**407**	**70.1**	**-33.2**	**0**	**0**	**497**
2009 LDPE-coated plate (12.1 g), equiv strength, max decomp							
Plate production	15.3	458	0	0	0	0	473
End-of-life	0	6.68	13.1	-86.0	540	-20.0	454
Total	**15.3**	**465**	**13.1**	**-86.0**	**540**	**-20.0**	**927**

Source: Franklin Associates, A Division of ERG

Table 2-27. Greenhouse Gas Emissions for Average Weight Sandwich-size Clamshells
(Pounds of CO2 Equivalents per 10,000 clamshells)

	Process	Fuel	WTE combustion emissions	Displaced kWh credit	LF methane	C02 equiv for C seq	Net CO2 eq
GPPS foam clamshell (4.8 g)							
Clamshell production	54.8	430	0	0	0	0	484
End-of-life	0	6.97	71.6	-33.9	0	0	44.7
Total	**54.8**	**437**	**71.6**	**-33.9**	**0**	**0**	**529**
Fluted paperboard clamshell (10.2 g), max decomp							
Clamshell production	3.60	523	0	0	0	0	527
End-of-life	0	5.58	0	-56.1	317	-112	154
Total	**3.60**	**529**	**0**	**-56.1**	**317**	**-112**	**681**
Solid PLA clamshell (23.3 g)							
Clamshell production	261	2,046	0	0	0	0	2,307
End-of-life	0	12.9	0	-75.0	0	-753	-815
Total	**261**	**2,059**	**0**	**-75.0**	**0**	**-753**	**1492**
Fluted paperboard clamshell (10.2 g), 50% decomp							
Clamshell production	3.60	523	0	0	0	0	527
End-of-life	0	5.58	0	-42.4	159	-200	-78.1
Total	**3.60**	**529**	**0**	**-42.4**	**159**	**-200**	**448**
Fluted paperboard clamshell (10.2 g), 0% decomp							
Clamshell production	3.60	523	0	0	0	0	527
End-of-life	0	5.58	0	-28.7	0	-288	-311
Total	**3.60**	**529**	**0**	**-28.7**	**0**	**-288**	**216**

Source: Franklin Associates, A Division of ERG

The first two columns of Tables 2-23 through 2-26 show the total process and fuel-related CO_2 eq for all steps from raw material extraction through placement of postconsumer foodservice items in a landfill or transport to a waste combustion facility. For PS foam products, there are process-related greenhouse gas emissions from resin production processes as well as from the production and destruction of blowing agent used in foam product manufacture. Process GHG emission are low for paperboard products, while for PLA products there are process emissions associated with agricultural operations.

The effect of end-of-life management of foodservice products is shown in the remaining columns of the tables. The third column shows the CO_2 eq *additions* from combustion of 20 percent of disposed foodservice items. The fourth column shows the CO_2 eq *credit* for the grid electricity that is displaced by the electricity produced with energy recovered from WTE combustion of postconsumer products and WTE combustion of landfill gas recovered from decomposition of landfilled paperboard products. Emissions from combustion of biomass-derived paperboard and PLA are considered carbon neutral, while emissions from combustion of fossil-derived polystyrene and LDPE resin coatings on paperboard products contribute to net CO_2 eq.

Columns 5 and 6 of the GHG tables show the CO_2 eq associated with landfilling 80 percent of postconsumer foodservice products. Column 5 reports the estimated CO_2 eq from fugitive methane releases from decomposition of landfilled paperboard products. It is important to note that these are the *cumulative* releases of methane, which will occur over a period of years as the material slowly decomposes anaerobically in the landfill. (As noted in Chapter 1, CO_2 from combustion or decomposition of biomass-derived materials such as PLA and paperboard is considered carbon neutral and is not included in the CO_2 eq results.) Column 6 shows the CO_2 sequestration credit, based on the carbon content of landfilled biomass-derived material that does not decompose.

The final column of Tables 2-23 through 2-26 show the net CO_2 eq when the process CO_2 eq, fuel-related CO_2 eq, and end-of-life CO_2 eq are totaled. Figures 2-13a through 2-16a show the relative contributions of process emissions, fuel-related emissions, and end-of-life management emissions to total CO_2 eq, while Figures 2-13b through 2-16b show the net CO_2 eq when the three categories are added. In the net CO_2 figures, results for the PS systems are identified using red, while results for other materials are shown in blue.

Figure 2-13a. Greenhouse Gas Emissions for 16-oz Hot Cups
(lb CO2 eq per 10,000 average weight cups)

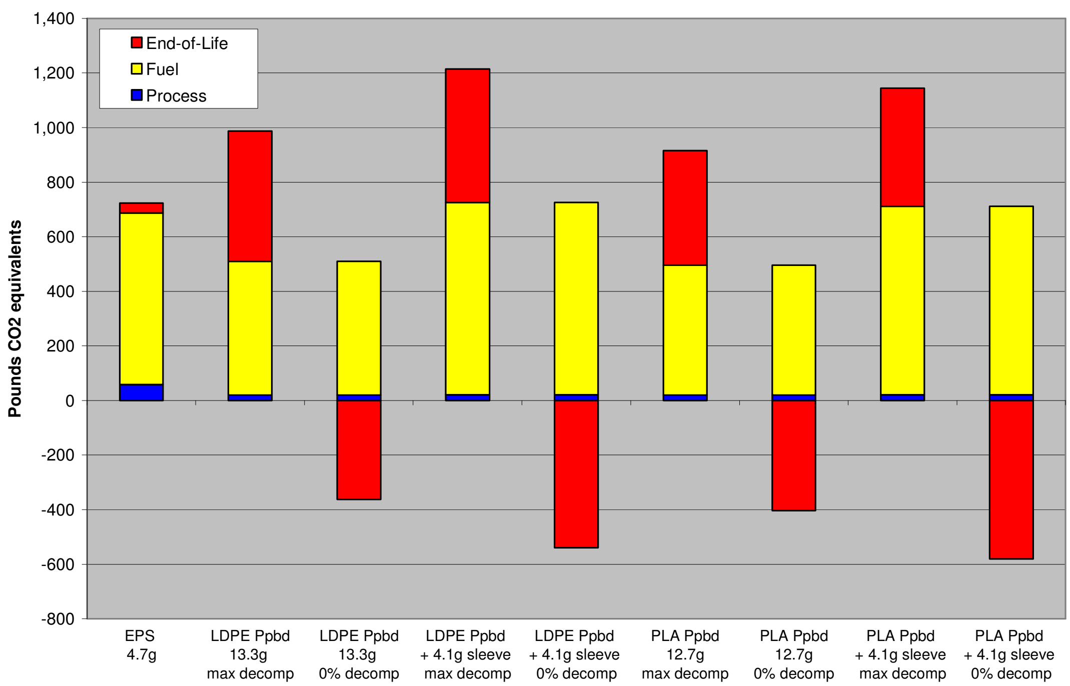


Figure 2-14a. Greenhouse Gas Emissions for 32-oz Cold Cups
(lb CO2 eq per 10,000 average weight cups)

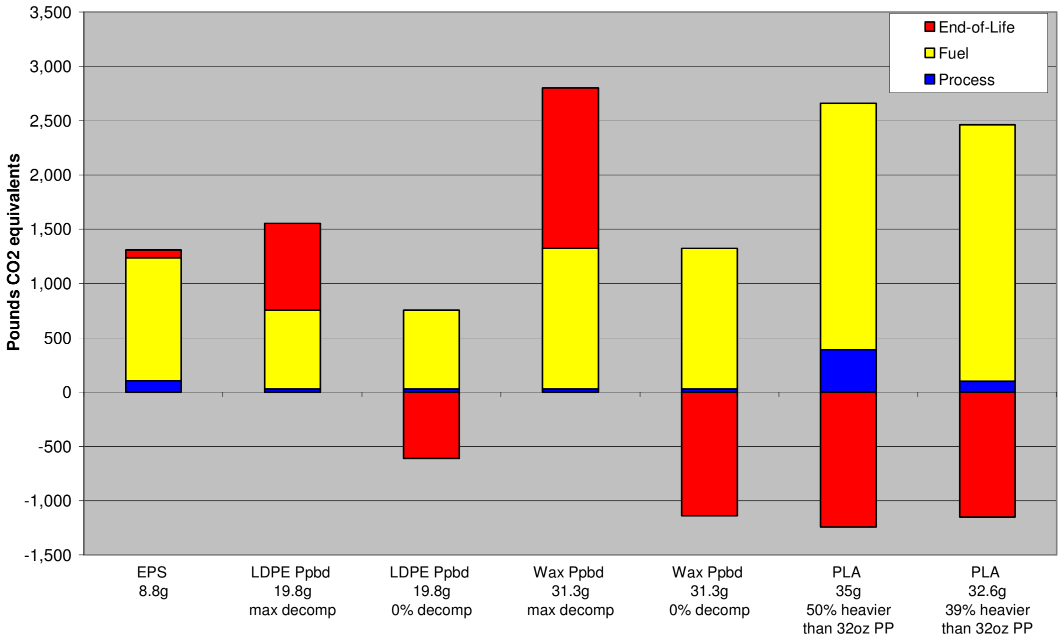


Figure 2-15a. Greenhouse Gas Emissions for 9-inch Plates
(lb CO2 eq per 10,000 average weight plates)

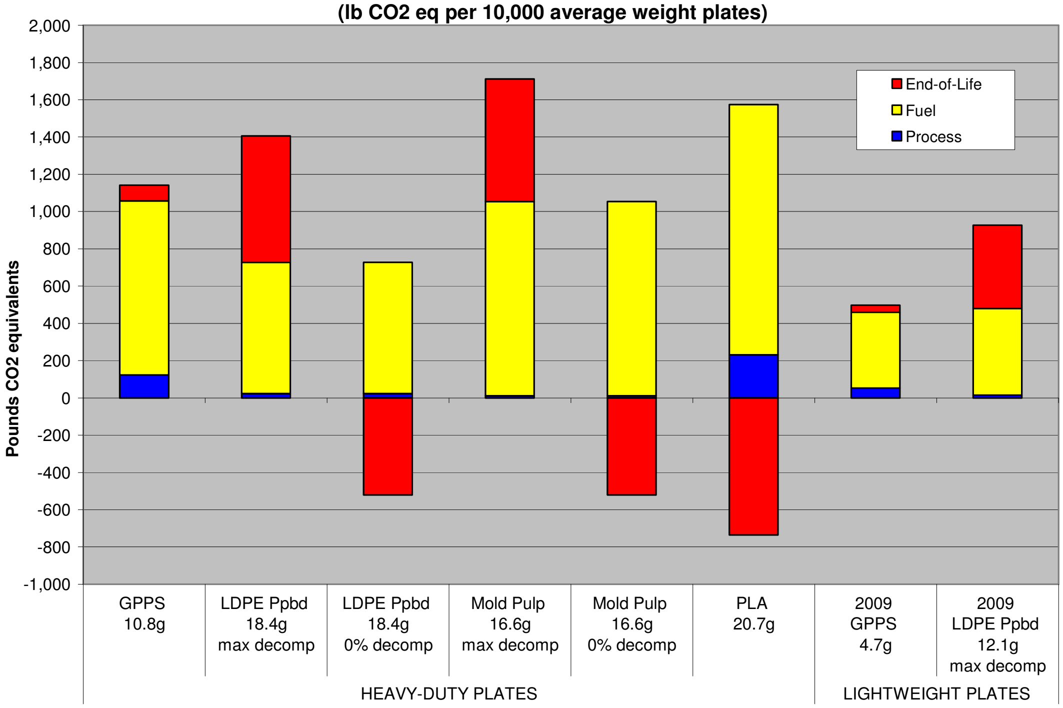


Figure 2-16a. Greenhouse Gas Emissions for Sandwich-size Clamshells
(lb CO2 eq per 10,000 average weight clamshells)

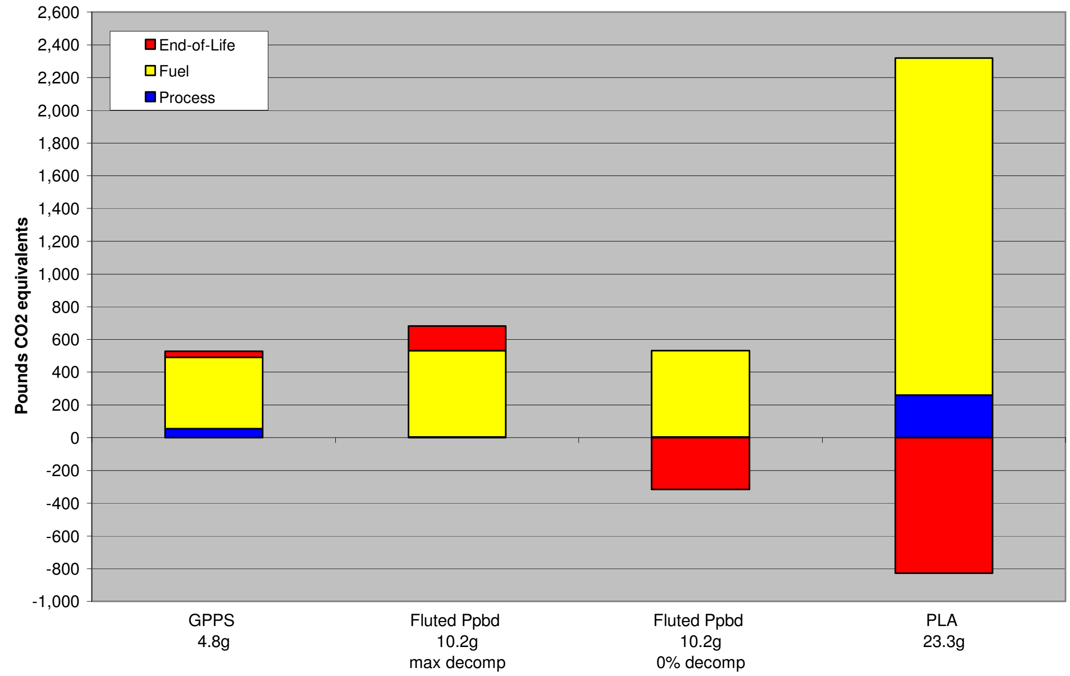


Figure 2-13b. Net Greenhouse Gas Emissions for 16-oz Hot Cups
(lb CO2 eq per 10,000 average weight cups)

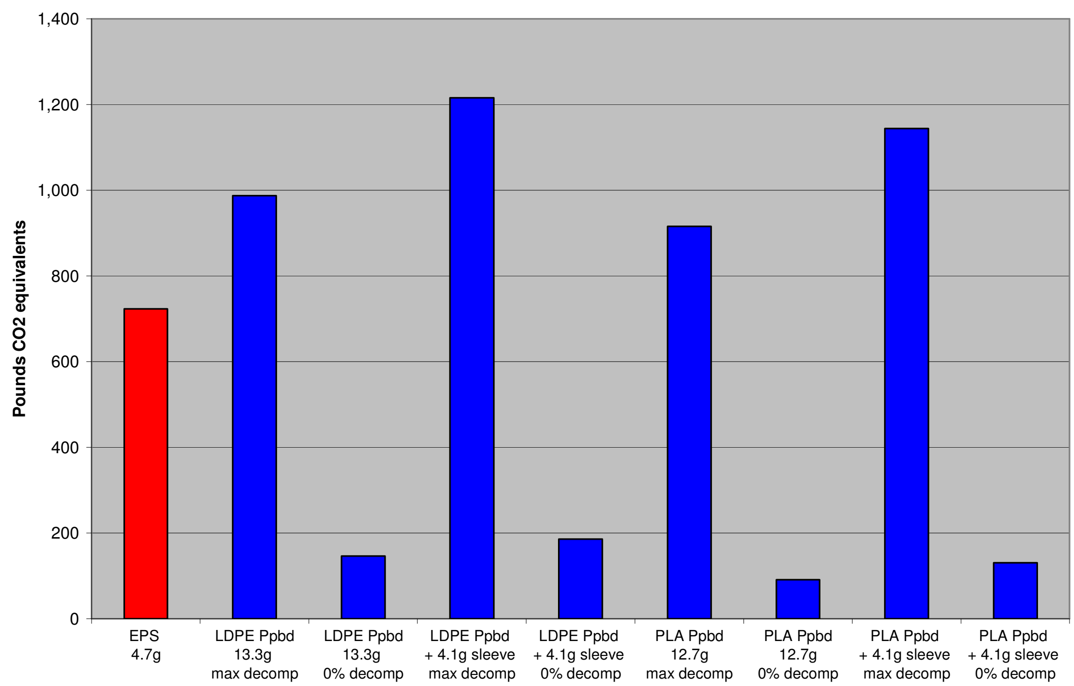


Figure 2-14b. Net Greenhouse Gas Emissions for 32-oz Cold Cups (lb CO2 eq per 10,000 average weight cups)

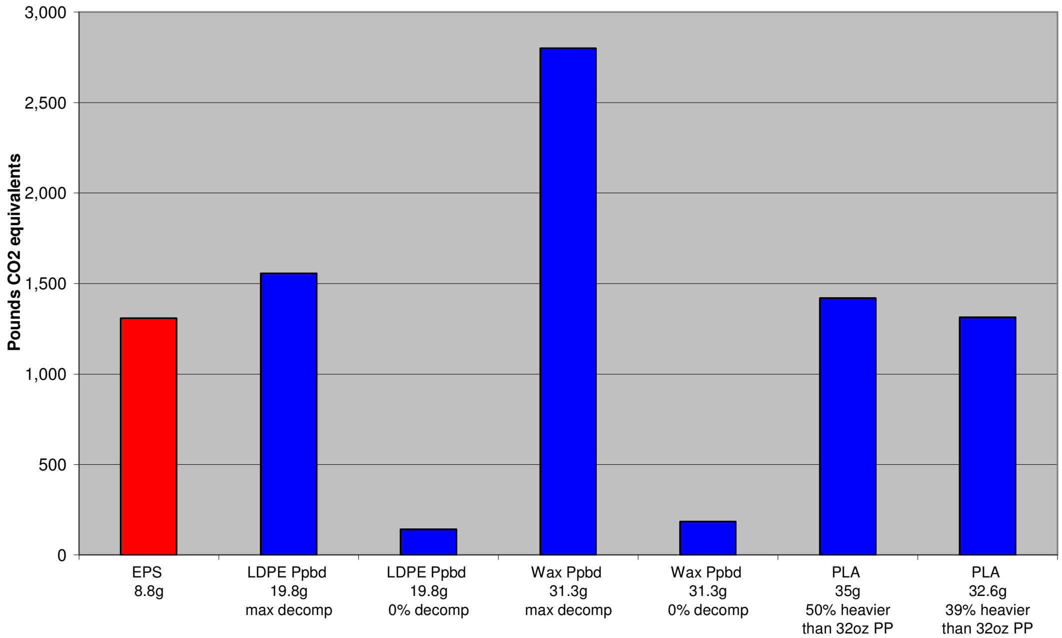


Figure 2-15b. Net Greenhouse Gas Emissions for 9-inch Plates (lb CO2 eq per 10,000 average weight plates)

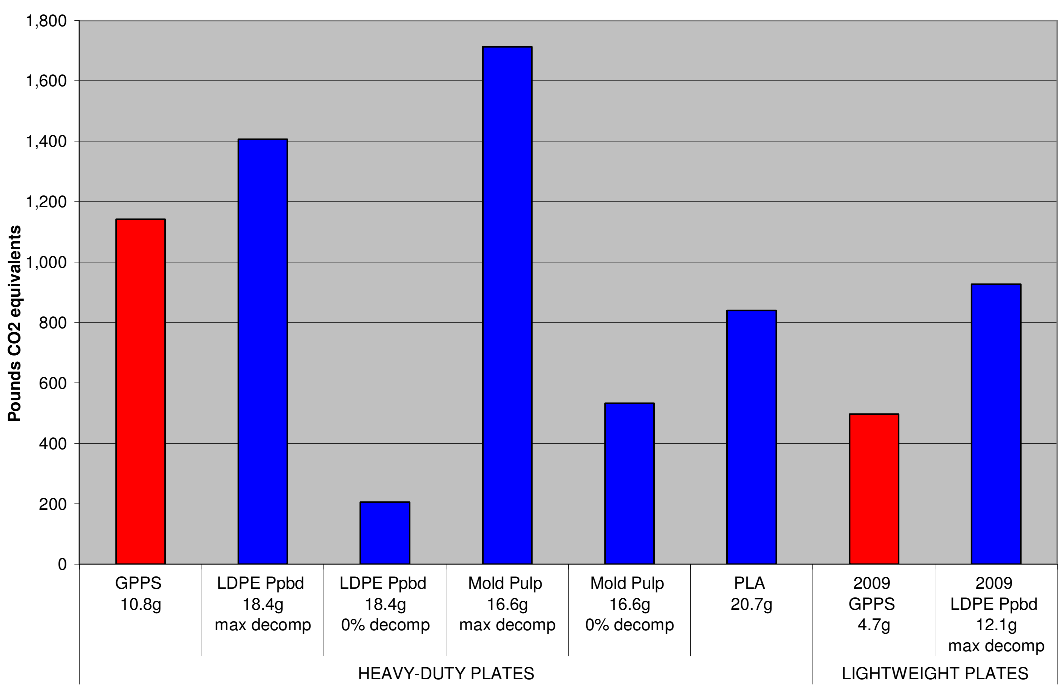
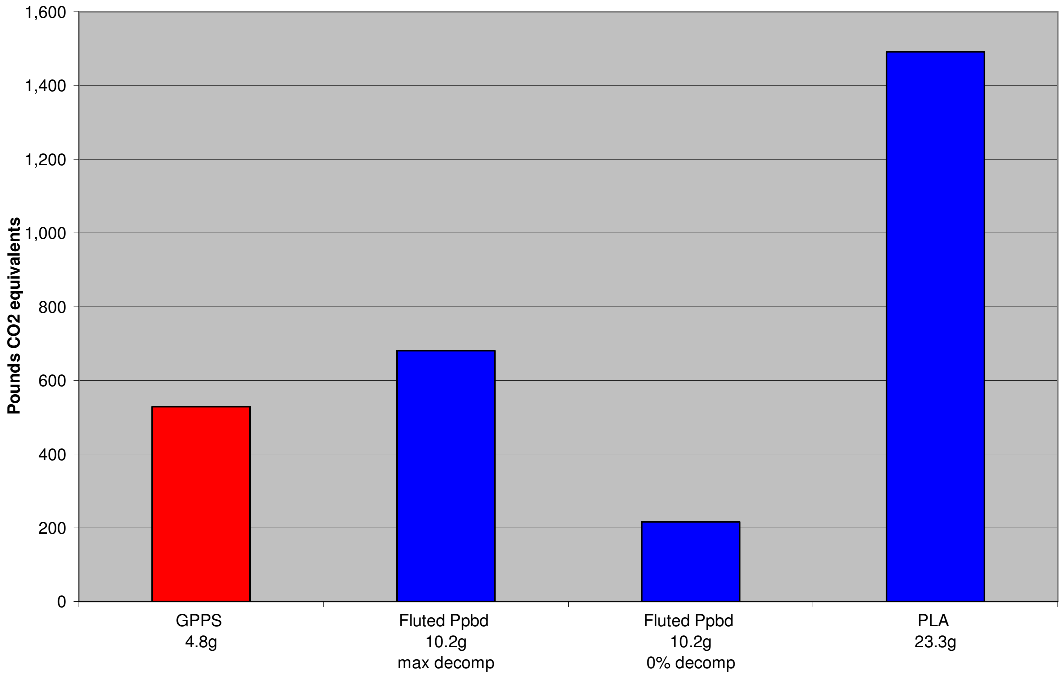


Figure 2-16b. Net Greenhouse Gas Emissions for Sandwich-size Clamshells (lb CO2 eq per 10,000 average weight clamshells)



The end-of-life CO_2 eq segments in Figures 2-14a through 2-16a show that end-of-life management results in a small net increase in CO_2 eq for PS foam products and a substantial net credit for solid PLA products. Both GPPS and PLA have a high carbon content and do not decompose to produce methane in landfills. For GPPS, the fossil CO_2 emissions from WTE combustion of postconsumer material are slightly greater than the CO_2 credit for grid electricity displaced by WTE electricity. However, for PLA products, the biomass CO_2 emissions from burning PLA are considered carbon neutral because the carbon content of PLA is from carbon dioxide taken up from the atmosphere by the corn plant. Therefore, WTE combustion of PLA products results in a net CO_2 credit due to the avoided fossil CO_2 eq for grid electricity that is displaced. In addition, there is a carbon sequestration credit for PLA that is landfilled, since landfilling permanently sequesters the carbon that was removed from the atmosphere by the corn plant and embodied in the PLA material.

The net GHG effect of end-of-life management of paperboard foodservice items depends on assumptions about decomposition and landfill gas management. The tables and figures show that maximum decomposition of the biomass carbon content results in a large net increase in end-of-life CO_2 eq associated with emissions of methane into the atmosphere. At maximum decomposition of bleached paperboard, there is little carbon sequestered in the portion of the material that does not decompose. However, if the bleached paperboard is assumed to decompose to only half of the maximum degree observed in landfill simulation experiments, there is only a small net increase in end-of-life CO_2 eq. For cup sleeves and clamshells, the unbleached kraft used in these products is less delignified than bleached kraft; therefore, less of the fiber decomposes and there is a small net carbon sequestration credit at 50 percent decomposition. At zero percent decomposition, no methane is produced, and all the biomass carbon in the paperboard products is sequestered, resulting in a large net CO_2 sequestration credit.

End-of-Life GHG Uncertainty. It is important to note that the end-of-life CO_2 eq estimates have a larger uncertainty than other LCI emissions data. Some of the modeling assumptions contributing to the uncertainty include the following:

- The CO_2 emissions from WTE combustion of postconsumer materials are estimated based on complete conversion of the carbon content of the material to CO_2.
- The end-of-life decomposition of paperboard products is modeled based on results from landfill simulation experiments designed to maximize decomposition. The ultimate degree of decomposition can be highly variable in actual landfills where moisture, temperature, and other factors differ from the experimental conditions.
- Results for bleached office paper decomposition were used to estimate decomposition of the bleached paper content of the coated paperboard products. There are no experimental landfill simulation studies on coated paperboard foodservice items, so it is unknown to what extent the coatings on these products affect the ultimate degree of decomposition of the paper fraction.
- Electricity offset credits are based on average efficiencies for converting combustion energy to electricity at municipal solid waste mass burn WTE combustion facilities and landfill gas WTE facilities. Actual efficiencies for individual energy recovery facilities will vary.
- Management of landfill methane is based on applying current landfill gas management practices to the cumulative methane emissions from decomposition of the material. However, the methane would be released gradually over many years, during which time landfill gas collection may be increased or WTE combustion of landfill gas may be increased.

To address the effects of some of these uncertainties on the end-of-life CO_2 eq for paperboard products, additional sensitivity analysis is presented in Chapter 3.

Process and Fuel-related GHG by Substance. Tables 2-27 through 2-30 present detail on the process and fuel-related CO_2 eq by substance. The results in this table (which correspond to the emissions shown in the first two columns of Tables 2-23 through 2-26) include cradle-to-production results for foodservice products, including transport to a landfill or combustion facility but excluding estimated end-of-life GHG effects associated with combustion or landfill decomposition. Thus, the results in Tables 2-27 through 2-30 do not include any emissions associated with EMR of products, since EMR does not result in emissions unless the material is burned, e.g., in WTE combustion facilities at end of life. The tables shows that fossil carbon dioxide is the main contributor to process and fuel-related CO_2 eq for PS foam and paperboard systems, accounting for at least 88 percent of the total CO_2 eq for all the systems studied. Methane emissions for PS foam products account for approximately 10 percent of the total process and fuel-related CO_2 eq and are largely associated with the extraction and processing of natural gas, used as one of the material inputs to polystyrene resin production and production of the pentane blowing agent. For the solid PLA systems, fossil carbon dioxide is also the largest contributor to the process and fuel-related CO_2 eq, but nitrous oxide emissions account for about 4 percent of the total. The nitrous oxide emissions are mainly associated with agricultural operations.

Table 2-28. Process and Fuel-Related Greenhouse Gas Contributions by Substance for Average Weight 16-oz Hot Cups (Pounds of CO2 Equivalents per 10,000 cups, excluding estimates of GWP for end-of-life management)

	Fossil CO2*	Methane	Nitrous Oxide	Total Process + Fuel CO2 eq	Percent
EPS foam cup (4.7 g)					
Cup production	613	62.7	3.48	680	99.0%
End-of-life	6.55	0.20	0.072	6.82	1.0%
Total	**620**	**62.9**	**3.55**	**686**	
Percent by Substance	**90.3%**	**9.2%**	**0.5%**	**100.0%**	
LDPE-coated ppbd cup (13.3 g), max decomp					
Cup production	443	36.5	22.4	502	98.6%
End-of-life	7.05	0.22	0.078	7.35	1.4%
Total	**450**	**36.7**	**22.4**	**509**	
Percent by Substance	**88.4%**	**7.2%**	**4.4%**	**100.0%**	
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), max decomp					
Cup + sleeve production	639	45.8	30.1	715	98.6%
End-of-life	10.1	0.31	0.11	10.5	1.4%
Total	**650**	**46.1**	**30.2**	**726**	
Percent by Substance	**89.5%**	**6.3%**	**4.2%**	**100.0%**	
PLA-coated ppbd cup (12.7 g), max decomp					
Cup production	437	26.6	24.8	488	98.6%
End-of-life	6.73	0.21	0.075	7.02	1.4%
Total	**444**	**26.8**	**24.9**	**495**	
Percent by Substance	**89.6%**	**5.4%**	**5.0%**	**100.0%**	
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), max decomp					
Cup + sleeve production	633	35.9	32.6	702	98.6%
End-of-life	9.75	0.30	0.11	10.2	1.4%
Total	**643**	**36.2**	**32.7**	**712**	
Percent by Substance	**90.3%**	**5.1%**	**4.6%**	**100.0%**	
LDPE-coated ppbd cup (13.3 g), 50% decomp					
Cup production	443	36.5	22.4	502	98.6%
End-of-life	7.05	0.22	0.078	7.35	1.4%
Total	**450**	**36.7**	**22.4**	**509**	
Percent by Substance	**88.4%**	**7.2%**	**4.4%**	**100.0%**	
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), 50% decomp					
Cup + sleeve production	639	45.8	30.1	715	98.6%
End-of-life	10.1	0.31	0.11	10.5	1.4%
Total	**650**	**46.1**	**30.2**	**726**	
Percent by Substance	**89.5%**	**6.3%**	**4.2%**	**100.0%**	
PLA-coated ppbd cup (12.7 g), 50% decomp					
Cup production	437	26.6	24.8	488	98.6%
End-of-life	6.73	0.21	0.075	7.02	1.4%
Total	**444**	**26.8**	**24.9**	**495**	
Percent by Substance	**89.6%**	**5.4%**	**5.0%**	**100.0%**	
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), 50% decomp					
Cup + sleeve production	633	35.9	32.6	702	98.6%
End-of-life	9.75	0.30	0.11	10.2	1.4%
Total	**643**	**36.2**	**32.7**	**712**	
Percent by Substance	**90.3%**	**5.1%**	**4.6%**	**100.0%**	
LDPE-coated ppbd cup (13.3 g), 0% decomp					
Cup production	443	36.5	22.4	502	98.6%
End-of-life	7.05	0.22	0.078	7.35	1.4%
Total	**450**	**36.7**	**22.4**	**509**	
Percent by Substance	**88.4%**	**7.2%**	**4.4%**	**100.0%**	
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g), 0% decomp					
Cup + sleeve production	639	45.8	30.1	715	98.6%
End-of-life	10.1	0.31	0.11	10.5	1.4%
Total	**650**	**46.1**	**30.2**	**726**	
Percent by Substance	**89.5%**	**6.3%**	**4.2%**	**100.0%**	
PLA-coated ppbd cup (12.7 g), 0% decomp					
Cup production	437	26.6	24.8	488	98.6%
End-of-life	6.73	0.21	0.075	7.02	1.4%
Total	**444**	**26.8**	**24.9**	**495**	
Percent by Substance	**89.6%**	**5.4%**	**5.0%**	**100.0%**	
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g), 0% decomp					
Cup production	633	35.9	32.6	702	98.6%
End-of-life	9.75	0.30	0.11	10.2	1.4%
Total	**643**	**36.2**	**32.7**	**712**	
Percent by Substance	**90.3%**	**5.1%**	**4.6%**	**100.0%**	

* None of the fossil CO2 reported in this table is associated with the energy of material resource in plastic resins. Column 3 of Table 2-24 includes CO2 emissions associated with the energy of material resource content of fossil-derived plastic material that is burned at end-of-life.

Source: Franklin Associates, A Division of ERG

Table 2-29. Process and Fuel-Related Greenhouse Gas Contributions by Substance for Average Weight 32-oz Cold Cups (Pounds of CO2 Equivalents per 10,000 cups, excluding estimates of GWP for end-of-life management)

	Fossil CO2*	Methane	Nitrous Oxide	Total Process + Fuel CO2 eq	Percent
EPS foam cup (8.8 g)					
Cup production	1,106	115	6.24	1,227	99.0%
End-of-life	12.3	0.38	0.13	12.8	1.0%
Total	**1,119**	**115**	**6.37**	**1,240**	
Percent by Substance	**90.2%**	**9.3%**	**0.5%**	**100.0%**	
LDPE-coated ppbd cup (19.8 g), max decomp					
Cup production	653	53.4	37.0	743	98.4%
End-of-life	11.6	0.36	0.13	12.1	1.6%
Total	**665**	**53.7**	**37.1**	**755**	
Percent by Substance	**88.0%**	**7.1%**	**4.9%**	**100.0%**	
Wax-coated ppbd cup (31.3 g), max decomp					
Cup production	1,160	77.2	68.4	1,306	98.7%
End-of-life	16.6	0.52	0.18	17.3	1.3%
Total	**1,177**	**77.7**	**68.6**	**1,323**	
Percent by Substance	**88.9%**	**5.9%**	**5.2%**	**100.0%**	
Solid PLA cup, based on sample weights (35 g)					
Cup production	2,382	157	103	2,641	99.3%
End-of-life	18.5	0.58	0.21	19.3	0.7%
Total	**2,400**	**157**	**103**	**2,661**	
Percent by Substance	**90.2%**	**5.9%**	**3.9%**	**100.0%**	
Solid PLA cup, calculated using resin densities (32.4 g)					
Cup production	2,205	145.3	95	2,446	99.3%
End-of-life	17.1	0.53	0.19	17.9	0.7%
Total	**2,222**	**145.8**	**95**	**2,464**	
Percent by Substance	**90.2%**	**5.9%**	**3.9%**	**100.0%**	
LDPE-coated ppbd cup (19.8 g), 50% decomp					
Cup production	653	53.4	37.0	743	98.4%
End-of-life	11.6	0.36	0.13	12.1	1.6%
Total	**665**	**53.7**	**37.1**	**755**	
Percent by Substance	**88.0%**	**7.1%**	**4.9%**	**100.0%**	
Wax-coated ppbd cup (31.3 g), 50% decomp					
Cup production	1,160	77.2	68.4	1,306	98.7%
End-of-life	16.6	0.52	0.18	17.3	1.3%
Total	**1,177**	**77.7**	**68.6**	**1,323**	
Percent by Substance	**88.9%**	**5.9%**	**5.2%**	**100.0%**	
LDPE-coated ppbd cup (19.8 g), 0% decomp					
Cup production	653	53.4	37.0	743	98.4%
End-of-life	11.6	0.36	0.13	12.1	1.6%
Total	**665**	**53.7**	**37.1**	**755**	
Percent by Substance	**88.0%**	**7.1%**	**4.9%**	**100.0%**	
Wax-coated ppbd cup (31.3 g), 0% decomp					
Cup production	1,160	77.2	68.4	1,306	98.7%
End-of-life	16.6	0.52	0.18	17.3	1.3%
Total	**1,177**	**77.7**	**68.6**	**1,323**	
Percent by Substance	**88.9%**	**5.9%**	**5.2%**	**100.0%**	

* None of the fossil CO2 reported in this table is associated with the energy of material resource in plastic resins. Column 3 of Table 2-25 includes CO2 emissions associated with the energy of material resource content of fossil-derived plastic material that is burned at end-of-life.

Source: Franklin Associates, A Division of ERG

Table 2-30. Process and Fuel-Related Greenhouse Gas Contributions by Substance for Average Weight Heavy Duty 9-inch Plates (Pounds of CO2 Equivalents per 10,000 plates, excluding estimates of GWP for end-of-life management)

	Fossil CO2*	Methane	Nitrous Oxide	Total Process + Fuel CO2 eq	Percent
GPPS foam plate (10.8 g)					
Plate production	933	104	4.98	1,041	98.5%
End-of-life	15.1	0.47	0.16	15.7	1.5%
Total	**948**	**104**	**5.14**	**1,057**	
Percent by Substance	**89.7%**	**9.8%**	**0.5%**	**100.0%**	
LDPE-coated plate (18.4 g), max decomp					
Plate production	638	48.2	32.0	718	98.6%
End-of-life	9.72	0.30	0.11	10.1	1.4%
Total	**647**	**48.5**	**32.1**	**728**	
Percent by Substance	**88.9%**	**6.7%**	**4.4%**	**100.0%**	
Molded pulp plate (16.6 g), max decomp					
Plate production	947	54.5	43.8	1,046	99.2%
End-of-life	7.97	0.25	0.089	8.31	0.8%
Total	**955**	**54.8**	**43.9**	**1,054**	
Percent by Substance	**90.6%**	**5.2%**	**4.2%**	**100.0%**	
Solid PLA plate (20.7 g)					
Plate production	1,410	92.9	61	1,564	99.3%
End-of-life	11.0	0.34	0.12	11.4	0.7%
Total	**1,421**	**93.3**	**61**	**1,576**	
Percent by Substance	**90.2%**	**5.9%**	**3.9%**	**100.0%**	
LDPE-coated plate (18.4 g), 50% decomp					
Plate production	638	48.2	32.0	718	98.6%
End-of-life	9.72	0.30	0.11	10.1	1.4%
Total	**647**	**48.5**	**32.1**	**728**	
Percent by Substance	**88.9%**	**6.7%**	**4.4%**	**100.0%**	
Molded pulp plate (16.6 g), 50% decomp					
Plate production	947	54.5	43.8	1,046	99.2%
End-of-life	7.97	0.25	0.089	8.31	0.8%
Total	**955**	**54.8**	**43.9**	**1,054**	
Percent by Substance	**90.6%**	**5.2%**	**4.2%**	**100.0%**	
LDPE-coated plate (18.4 g), 0% decomp					
Plate production	638	48.2	32.0	718	98.6%
End-of-life	9.72	0.30	0.11	10.1	1.4%
Total	**647**	**48.5**	**32.1**	**728**	
Percent by Substance	**88.9%**	**6.7%**	**4.4%**	**100.0%**	
Molded pulp plate (16.6 g), 0% decomp					
Plate production	947	54.5	43.8	1,046	99.2%
End-of-life	7.97	0.25	0.089	8.31	0.8%
Total	**955**	**54.8**	**43.9**	**1,054**	
Percent by Substance	**90.6%**	**5.2%**	**4.2%**	**100.0%**	
LIGHT-WEIGHT PLATES					
2009 GPPS Foam Plate (4.7 g)					
Plate production	406	45.1	2.17	453	98.5%
End-of-life	6.55	0.20	0.072	6.82	1.5%
Total	**412**	**45.3**	**2.24**	**460**	
Percent by Substance	**89.7%**	**9.8%**	**0.5%**	**100.0%**	
2009 LDPE-coated plate (12.1 g), equiv strength, max decomp					
Plate production	420	31.8	21.1	473	98.6%
End-of-life	6.41	0.20	0.071	6.68	1.4%
Total	**427**	**32.0**	**21.2**	**480**	
Percent by Substance	**88.9%**	**6.7%**	**4.4%**	**100.0%**	

* None of the fossil CO2 reported in this table is associated with the energy of material resource in plastic resins. Column 3 of Table 2-26 includes CO2 emissions associated with the energy of material resource content of fossil-derived plastic material that is burned at end-of-life.

Source: Franklin Associates, A Division of ERG

Table 2-31. Process and Fuel-Related Greenhouse Gas Contributions by Substance for Average Weight Sandwich-size Clamshells (Pounds of CO2 Equivalents per 10,000 clamshells, excluding estimates of GWP for end-of-life management)

	Fossil CO2*	Methane	Nitrous Oxide	Total Process + Fuel CO2 eq	Percent
GPPS foam clamshell (4.8 g)					
Clamshell production	436	45.8	2.39	484	98.6%
End-of-life	6.69	0.21	0.073	6.97	1.4%
Total	**443**	**46.0**	**2.47**	**491**	
Percent by Substance	**90.1%**	**9.4%**	**0.5%**	**100.0%**	
Fluted paperboard clamshell (10.2 g), max decomp					
Clamshell production	484	22.1	20.4	527	99.0%
End-of-life	5.36	0.17	0.060	5.58	1.0%
Total	**489**	**22.3**	**20.4**	**532**	
Percent by Substance	**92.0%**	**4.2%**	**3.8%**	**100.0%**	
Solid PLA clamshell (23.3 g)					
Clamshell production	2,091	132	84	2,307	99.4%
End-of-life	12.3	0.38	0.14	12.9	0.6%
Total	**2,103**	**133**	**84**	**2,320**	
Percent by Substance	**90.6%**	**5.7%**	**3.6%**	**100.0%**	
Fluted paperboard clamshell (10.2 g), 50% decomp					
Clamshell production	484	22.1	20.4	527	99.0%
End-of-life	5.36	0.17	0.060	5.58	1.0%
Total	**489**	**22.3**	**20.4**	**532**	
Percent by Substance	**92.0%**	**4.2%**	**3.8%**	**100.0%**	
Fluted paperboard clamshell (10.2 g), 0% decomp					
Clamshell production	484	22.1	20.4	527	99.0%
End-of-life	5.36	0.17	0.060	5.58	1.0%
Total	**489**	**22.3**	**20.4**	**532**	
Percent by Substance	**92.0%**	**4.2%**	**3.8%**	**100.0%**	

* None of the fossil CO2 reported in this table is associated with the energy of material resource in plastic resins. Column 3 of Table 2-27 includes CO2 emissions associated with the energy of material resource content of fossil-derived plastic material that is burned at end-of-life.

Source: Franklin Associates, A Division of ERG

Water Use

The goal of the water use analysis was to identify water use for each unit process for each foodservice product and add the water use data to the unit process data sets to construct a full life cycle model of water use for each product system. However, it was not possible to meet this goal.

Although water use is increasingly becoming a focus in life cycle assessments, reliable and complete water use data are currently not available on a unit process level for many industrial processes and materials. This results in data gaps when attempting to construct cradle-to-product models for product systems on a unit process basis. In addition, available water data may not clearly distinguish between the type of use (process water, cooling water), source of the water used (groundwater, river, lake, ocean, etc.), or whether the water is recirculated or consumed. Without differentiation between consumptive and non-consumptive uses of water, the water results shown throughout this report are referred to as water *use* rather than water *consumption*.

With the lack of consistency and detail in how water use is reported, different water use data sets for the same process or material can show wide variations. For example, a data set that reports only consumptive use of cooling water might show much lower water use than a data set for the same process that also includes the volume of cooling water that recirculates through manufacturing equipment. Therefore, the water use results presented here have a higher uncertainty than other life cycle inventory results. The data sources, assumptions, and limitations of the water use results are described in more detail in Appendix A.

For plastic resins and resin coatings on paperboard products, cradle-to-resin water use data from PlasticsEurope Ecoprofiles was used. The water use data in Ecoprofiles is fully aggregated data that includes process water use, cooling water used for the processes, and cooling water associated with production of the electricity used in the processes. Because similar technologies are used for production of resins in the U.S. and in Europe, it is assumed that the Ecoprofiles data provide a good approximation of water use for U.S. resin production.

Several sources of water use data for paperboard production were evaluated, and all reported use of substantial volumes of water for process water and cooling. The water modeling for paperboard foodservice products in this analysis is based on Ecoinvent data sets for water use for production of pulp and water use for production of paper from pulp. These were the best-documented data sets available and were similar in overall water requirements to the other data sets evaluated.

The water use modeling for PLA was based on NatureWorks Ingeo data published as a rolled-up cradle-to-resin data set in the U.S. LCI Database. The NatureWorks data include water used for corn irrigation, water used in corn wet milling processes (allocated among the wet mill coproducts), and water used in PLA production. In the Ingeo cradle-to-resin dataset, about 44 percent of the reported water use is irrigation water, 34 percent is water used in processes that convert the corn to PLA, and about 23 percent is cooling water.

The corn irrigation water use included in the NatureWorks data set is specific to the Nebraska and Iowa counties that supply corn to the Blair, Nebraska Ingeo plant. Only 9.4 percent of the corn acreage in these counties is irrigated, compared to about 60 percent of all corn acreage in Nebraska. In addition, the water use per irrigated acre for these counties is lower than the average water use per irrigated corn acre, because there is more rainfall in eastern Nebraska and western Iowa compared to other corn-growing regions of the Midwest. The average amount of water applied per irrigated acre for the Blair plant's supplying counties was reported by NatureWorks as 127 mm (5 inches). In contrast, recent U.S. Department of Agriculture Farm and Ranch Irrigation Surveys reported averages of 14.4 inches of water per irrigated acre of Nebraska corn in 2003 and 9.6 inches of water per irrigated acre of Nebraska corn in 2008. Different sourcing for the corn used for PLA could have a significant effect on the water use results.

The results shown in the tables and figures include process water and cooling water that is directly used in producing the foodservice product materials, as well as cooling water for production of the electricity used in these processes. Further description of electricity cooling water use is provided in Appendix A. Data on cooling water use by foodservice product converting equipment was not available for all types of converting processes, and equipment cooling water is generally recirculated in closed-loop systems; therefore, for the operations used to convert paperboard, PS resin, and PLA resin into finished products, only electricity-related water use is included. Cooling water use per pound of product is higher for production of PS foam products and PLA products compared to paperboard products, since molding and thermoforming of resins requires more electricity compared to the processes used to convert paperboard into cups, plates, and clamshells.

Water use results for polystyrene foam products are dominated by cooling water, which includes the cooling water in the aggregated cradle-to-resin data as well as the cooling water associated with the electricity used to convert the resin into foodservice products. Process water makes a small contribution to the total water use for PS foam products, but accounts for 35 to 40 percent of total water use for paperboard product systems. Water use results for average weight paperboard products are 20 to 30 percent higher than water use for corresponding average weight PS foam products.

Water use results are 2 to 4 times higher for PLA products compared to corresponding PS foam products. For solid PLA products, the process water use (including irrigation) is about 14 percent of the total water use. The differences in the weights of the solid PLA and PS foam products are a significant driver for the comparative water use results.

Because the water use results in this analysis are largely based on aggregated cradle-to-material data sets and estimates based on literature, it is difficult to assess the reliability or comparability of the water use results for the various product systems. Every effort was made to provide corresponding coverage of water use for each product system; however, without access to supporting unit process data it was not possible to ensure that cradle-to-material data sets for different materials were derived using consistent methodologies. Therefore, the comparative water use results in this report have a high degree of uncertainty. It is clear that there is a need for transparent, unit process-level water use data for life cycle modeling.

Table 2-32. Water Use for Average Weight 16-oz Hot Cups
(Gallons per 10,000 cups)

	Cooling Water	Process Water	Total
EPS foam cup (4.7 g)	4,673	75.2	**4,748**
LDPE-coated ppbd cup (13.3 g)	3,979	2,173	**6,152**
LDPE-coated ppbd cup (13.3 g) with sleeve (4.1 g)	5,212	2,883	**8,095**
PLA-coated ppbd cup (12.7 g)	4,120	2,228	**6,348**
PLA-coated ppbd cup (12.7 g) with sleeve (4.1 g)	5,352	2,939	**8,291**

Source: Franklin Associates, A Division of ERG

Table 2-33. Water Use for Average Weight 32-oz Cold Cups
(Gallons per 10,000 cups)

	Cooling Water	Process Water	Total
EPS foam cup (8.8 g)	8,301	139	**8,441**
LDPE-coated ppbd cup (19.8 g)	5,628	3,650	**9,278**
Wax-coated ppbd cup (31.3 g)	10,506	6,764	**17,271**
Solid PLA cup, based on sample weights (35 g)	20,581	3,413	**23,994**
Solid PLA cup, calculated using resin densities (32.4	19,057	3,160	**22,217**

Source: Franklin Associates, A Division of ERG

Table 2-34. Water Use for Average Weight Heavy Duty 9-inch Plates
(Gallons per 10,000 plates)

	Cooling Water	Process Water	Total
GPPS foam plate (10.8 g)	7,216	249	**7,466**
LDPE-coated plate (18.4 g)	5,798	3,100	**8,898**
Molded pulp plate (16.6 g)	5,821	3,196	**9,017**
Solid PLA plate (20.7 g)	12,187	2,021	**14,208**

Source: Franklin Associates, A Division of ERG

Table 2-35. Water Use for Average Weight Sandwich-size Clamshells
(Gallons per 10,000 clamshells)

	Cooling Water	Process Water	Total
GPPS foam clamshell (4.8 g)	3,761	112	**3,873**
Fluted paperboard clamshell (10.2 g)	3,169	1,783	**4,951**
Solid PLA clamshell (23.3 g)	13,721	2,275	**15,996**

Source: Franklin Associates, A Division of ERG

Figure 2-17. Gallons of Water Used for 16-oz Hot Cups (10,000 average weight cups)

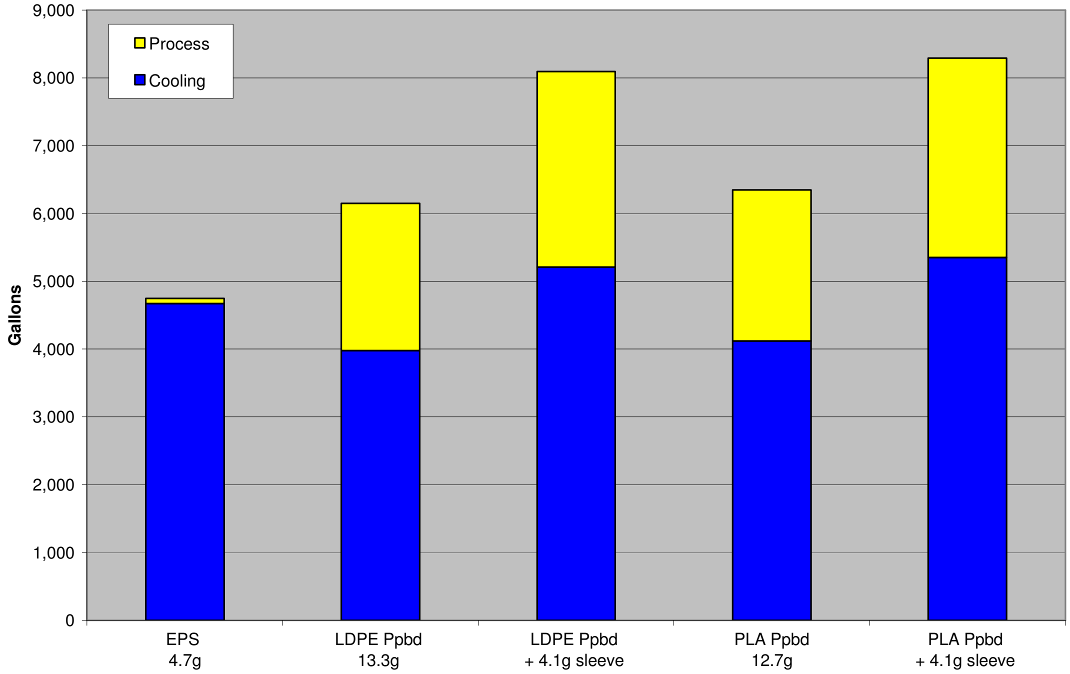


Figure 2-18. Gallons of Water Used for 32-oz Cold Cups (10,000 average weight cups)

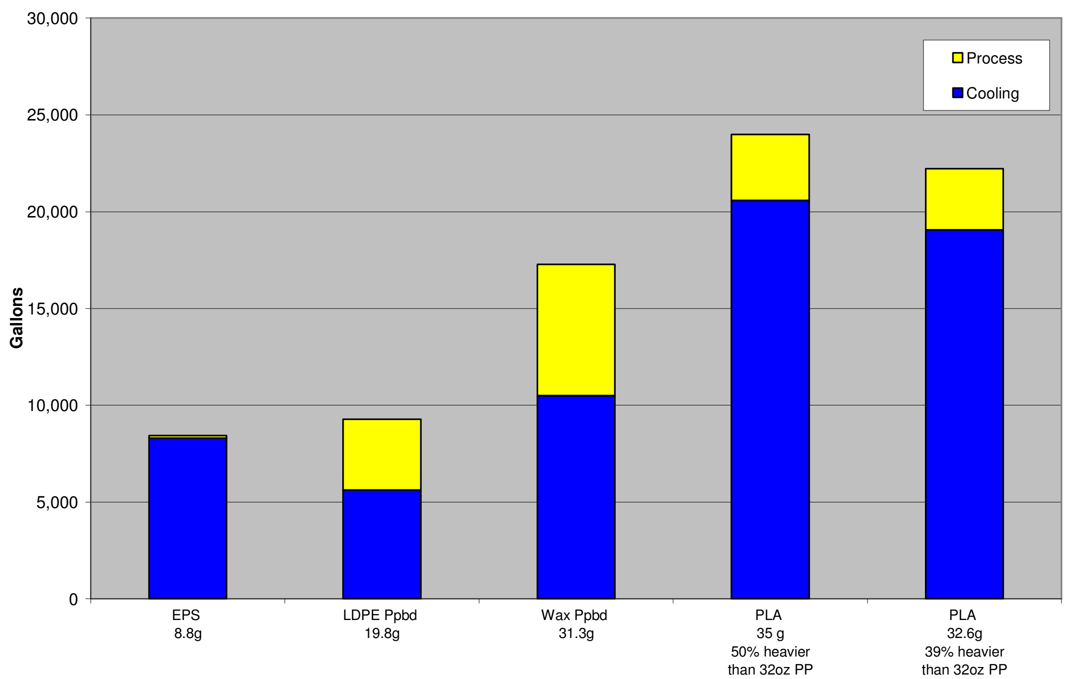


Figure 2-19 Gallons of Water Used for 9-inch Plates (10,000 average weight plates)

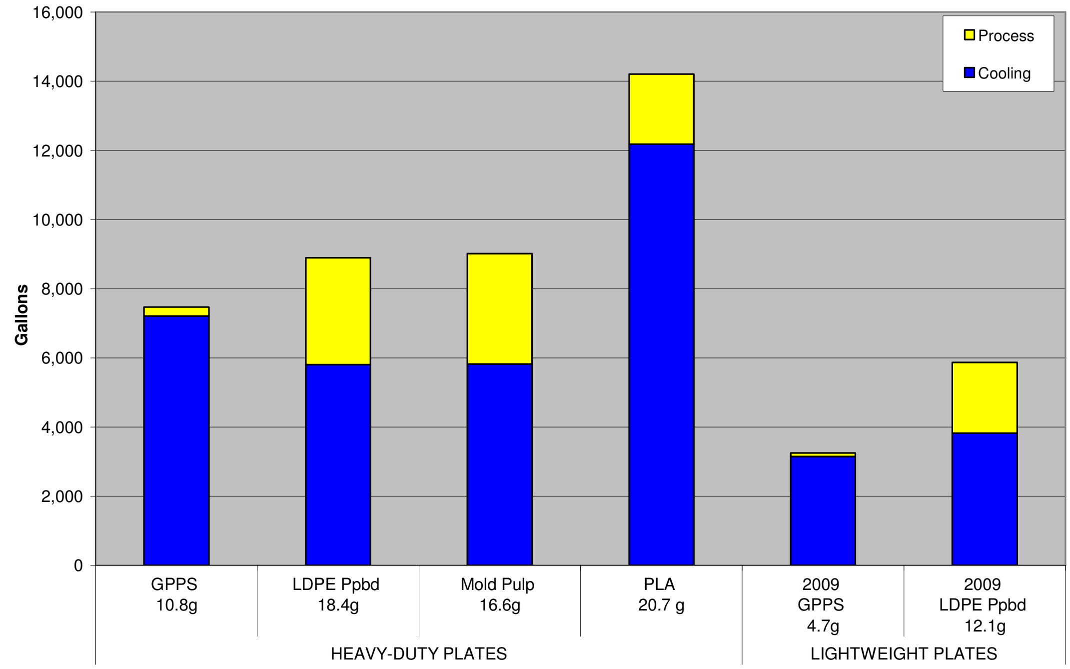
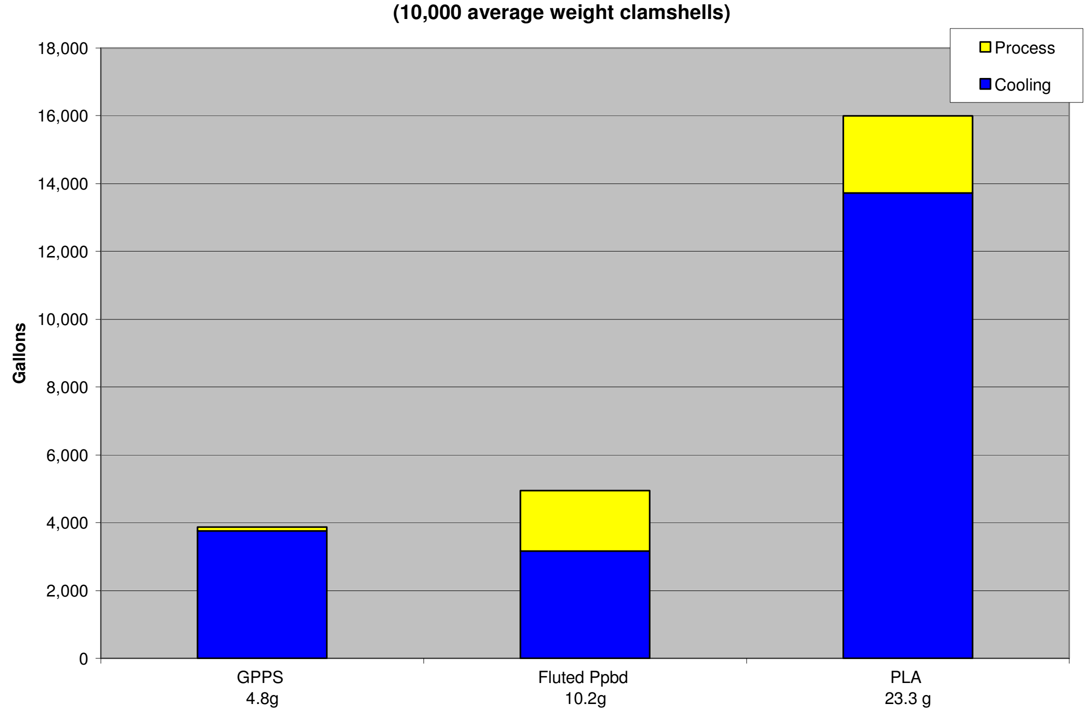


Figure 2-20. Gallons of Water Used for Sandwich-size Clamshells (10,000 average weight clamshells)



KEY OBSERVATIONS AND CONCLUSIONS

The observations and conclusions regarding energy, solid waste, water use and greenhouse gases are all sensitive to the assumptions and choices made in this study about

- Product weight
- Inclusion of bio-based EMR
- Solid waste reporting basis (by weight or by volume)
- Decomposition of products in landfills and management of methane produced from decomposition
- Exclusion of indirect land use change
- Corn irrigation practices
- Choice of allocation method.

The following observations and conclusions are based on the assumptions made in this study and apply to the specific product weights analyzed in this report. The results, observations, and conclusions should not be considered representative of the full range of product weights that may be available in the marketplace.

- **Influence of Product Weight on LCI Results:** The majority of the environmental burdens for producing each type of foodservice item is from the production of the materials used. Material production burdens for a product are calculated as the product of the burdens per pound of material multiplied by the pounds of material used in the product system. Many grades and weights of disposable foodservice products are available in the marketplace. As shown in Table ES-1, all paperboard and PLA products analyzed in this study are heavier than the corresponding average weight PS foam product. Comparisons of products with different weight ratios may yield different conclusions. This can be seen in the plate tables, where there are large differences in the results for average weight high-grade plates and results for lighter weight plates from a 2009 LCI study.

- **Energy:** For the product weights modeled, the total energy requirements for average PS foam products across the different product categories are generally lower than total energy requirements for the equivalent number of (heavier) PLA or paperboard products analyzed. Total energy requirements for LDPE-coated cold cups, LDPE-coated plates, and molded pulp plates are not significantly different from energy requirements for the corresponding PS products.

- **Net Energy Consumption:** A significant portion of the total energy requirements for each product is energy of material resource. Some of the EMR remains embodied in the postconsumer products that are sent to landfills at end of life. Some energy is also recovered from postconsumer materials that are managed by WTE combustion, as well as from WTE combustion of landfill gas produced from paperboard decomposition.

- **Solid Waste:** Comparative conclusions about solid waste differ depending whether the results are expressed in terms of weight or volume of waste. Postconsumer products account for the largest share of solid waste for each system. The plastic foam systems produce less *weight* of solid waste compared to heavier paperboard and PLA products. However, because of the low density of foam products, the differences in solid waste *volume* of postconsumer foam products and corresponding paperboard or solid resin products become relatively small for most product categories. For plates, heavy-duty PS foam plates produce a greater volume of solid waste than other types of heavy-duty plates; however, for the 2009 equivalent strength plate comparison, the PS foam and paperboard plates have very similar solid waste volumes.

- **Greenhouse Gas Results:** The majority of GHG emissions for most systems studied are associated with combustion of fossil fuels for process and transportation energy. For the PLA system, there are also significant process GHG emissions associated with nitrous oxide emissions from fertilizer use for corn. The end-of-life greenhouse gas results presented here should be considered more uncertain than other emissions data. End-of-life management results in a small net increase in GHG for PS foam products and a net GHG credit for PLA products. End-of-life results for paperboard products vary considerably depending on assumptions about decomposition. At maximum experimental decomposition levels, the overall effect of the estimated GHG additions and credits from end-of-life management is a large net increase in GHG for paperboard products. At lower decomposition rates, the net end-of-life GHG for paperboard products is much smaller, since less methane is released and more carbon is sequestered in undecomposed material. If the paperboard does not decompose, no methane is produced and all the biomass carbon in the paperboard product is sequestered, resulting in a large carbon sequestration credit.

- **Limitations of Water Use Data:** Because of a lack of unit process-level data on water use, the water use results in this analysis are largely based on aggregated cradle-to-material data sets and estimates based on literature. In addition, data sources did not distinguish between consumptive use of cooling water and recirculating use of cooling water. Every effort was made to provide corresponding coverage of water use for each product system; however, without access to the supporting unit process data, and lacking distinction between consumptive and non-consumptive uses of water, it was not possible to ensure that different cradle-to-material data sets were derived using consistent methodologies. Therefore, the comparative water use results in this report have a high degree of uncertainty.

- **Water Use Results:** Across the different product categories, water use for the average weight paperboard product in each category is 20 to 30 percent higher than for the corresponding average weight PS foam product, and water use for the solid PLA product is 2 to 4 times as high as for the corresponding PS foam product. The differences in the weights of the solid PLA and PS foam products are a significant driver for the comparative water use results.

CHAPTER 3

SENSITIVITY ANALYSIS ON END-OF-LIFE DECOMPOSITION OF PAPERBOARD PRODUCTS

BACKGROUND

As described in the Greenhouse Gas Results section in Chapter 2, assumptions about end-of-life decomposition and the fate of landfill gas can significantly affect the end-of-life GHG results for paperboard products. There is a limited amount of experimental data on decomposition of different types of paper under simulated landfill conditions, and no experimental data on decomposition of coated paperboard foodservice products was found. The coatings on paperboard foodservice products may inhibit or perhaps even prevent decomposition of the fiber content.

The data sources and methodology used to estimate maximum decomposition of bleached paperboard foodservice products were described in detail in the section "End of Life Management" in Chapter 1. The sensitivity analysis in this chapter examines the effect of reduced gas production from decomposed material and increased landfill oxidation of generated methane for several of the paperboard foodservice products evaluated in this report. Based on information from NatureWorks' website about the stability of landfilled PLA and the conditions required for successful composting of PLA, no modeling of landfill decomposition of PLA was included in this analysis.

SCENARIO RESULTS

The maximum potential landfill methane emissions calculated in Chapter 2 (designated "theor max" in the results figures) are based on the experimental degree of decomposition of the cellulose and hemicellulose fractions of the fiber and the theoretical amount of methane that would be produced if all the decomposed carbon produced an equimolar mixture of carbon dioxide and methane. However, in the Barlaz experiments, the measured amount of methane gas recovered from the bleached paper reactors was much lower than the amount that should have been produced based on the measured degree of decomposition of the cellulose and hemicellulose in the paper. The expected amount of methane for the measured degree of decomposition is 276 g methane/kg of paper, but the measured amount of methane was 155 g/kg of paper. It was not possible to determine the fate of the carbon that decomposed but that did not show up as measured methane, so it is unknown whether that carbon ultimately is released or sequestered. Therefore, the reader should be aware that the results labeled "expt max" in the results figures do not include a complete carbon balance. The "expt max" emissions are based on the measured experimental quantities of methane produced, and the sequestration credits are based on the carbon content of the undecomposed material, so the difference between the carbon in the residual material and the carbon content of the collected reactor gas is not accounted for.

Some of the methane generated from anaerobic decomposition of material in a landfill is reduced by the percentage of methane that oxidizes as it passes through the landfill cover. The landfill methane results in Chapter 2 are based on 2006 landfill methane data in the EPA's **Inventory of U.S. Greenhouse Gas Emissions and Sinks,** which uses the IPCC guideline of 10 percent as the default value for oxidation of landfill methane that is not captured or vented. However, some studies have suggested that a higher percentage of uncollected methane may oxidize as it migrates to the landfill surface.[33] The higher the percentage of uncollected methane that oxidizes in the landfill cover, the lower the CO_2 eq for landfilled paperboard products. A 36 percent oxidation rate[34] is used in the sensitivity analysis calculations. Since the oxidation rate is applied to the percentage of methane that is *not* flared or burned with energy recovery, landfill gas energy recovery calculations are not affected by the use of higher oxidation rates.

Results by category for the end-of-life (EOL) sensitivity scenarios are shown in Figure 3-1a for hot cups, Figure 3-2a for cold cups, and Figure 3-3a for plates. Net GHG results are shown in Figures 3-1b through 3-3b. In each figure the PS product results are shown as a reference point. A number of observations can be made:

- Using the experimental methane generation quantities from the Barlaz experiments results in much lower EOL GHG than using the theoretical amount of methane that should have been produced from the amount of material that decomposed in the experiments.
- A decreased degree of decomposition has a much larger effect on the EOL GHG compared to the effect of an increase in landfill methane oxidation from 10 percent to 36 percent.
- As decomposition and gas generation decrease and oxidation of the produced methane increases, less methane is released to the atmosphere and more carbon is sequestered in the undecomposed material, shifting the EOL GHG from a net increase to a net credit.
- Depending on the degree of end-of-life decomposition of landfilled paperboard, the amount of methane produced from decomposition, and the oxidation of the produced methane in the landfill, the net GHG results for paperboard products can be higher than or lower than PS foam products. Factors influencing decomposition and methane oxidation include temperature, moisture, and landfill cover soil type. These factors can vary widely from landfill to landfill, making it difficult to make general predictions about EOL GHG for paperboard products.
- Because the PS foam products do not decompose in landfills to produce methane, there is much less uncertainty in the EOL GHG estimates for PS foam products.

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33 Chanton, J. P.; Powelson, D. K.; Green, R.B. **Methane Oxidation in Landfill Cover Soils, is a 10% Default Value Reasonable?,** J Environ. Qual. 38:654-663 (2009).

34 Overall mean oxidation from all studies reviewed in the Chanton paper.

Figure 3-1a. Sensitivity Analysis on End-of-Life Greenhouse Gas for 16-oz Hot Cups (10,000 average weight cups)

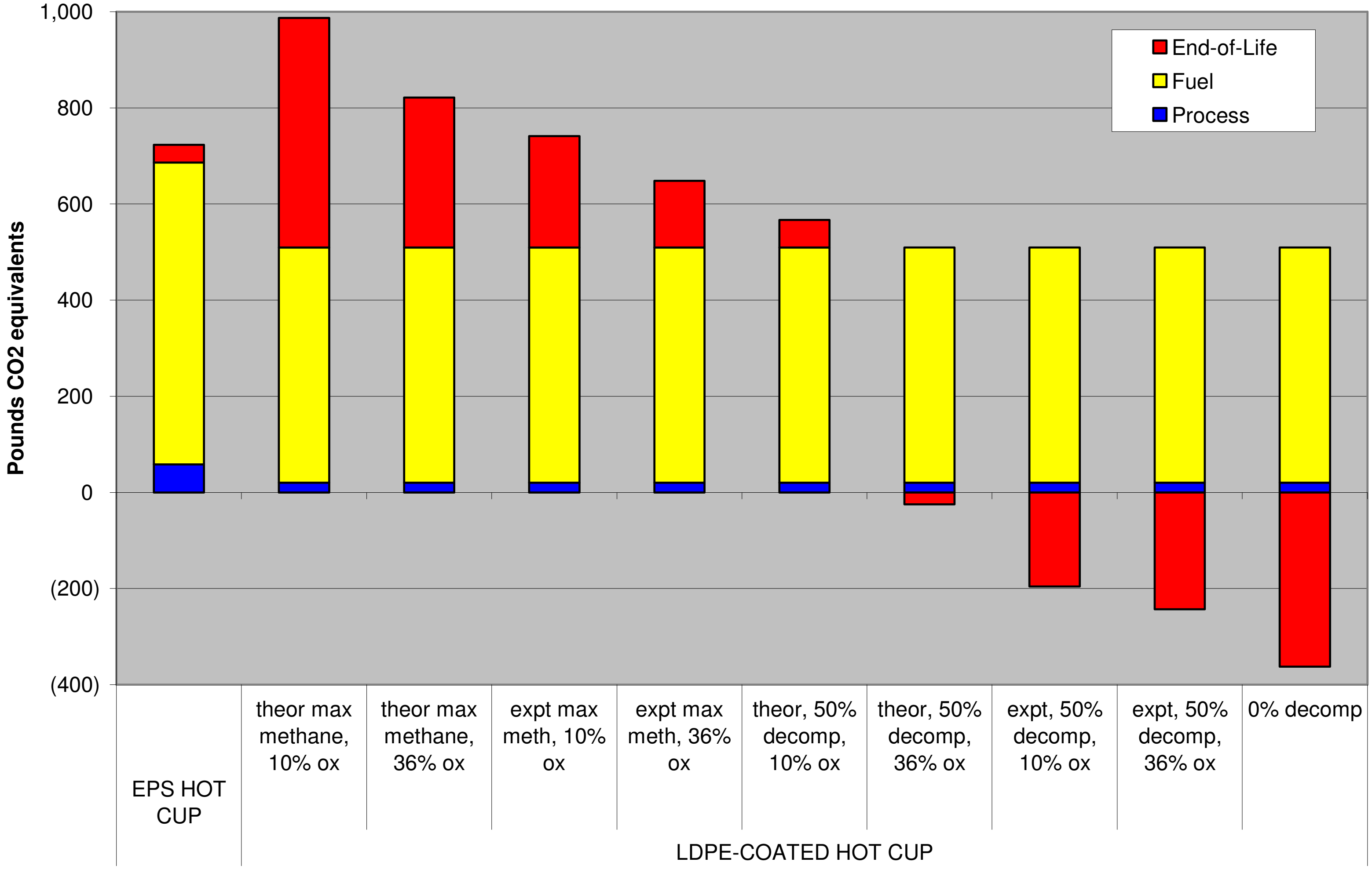


Figure 3-2a. Sensitivity Analysis on End-of-Life Greenhouse Gas for 32-oz Cold Cups (10,000 average weight cups)

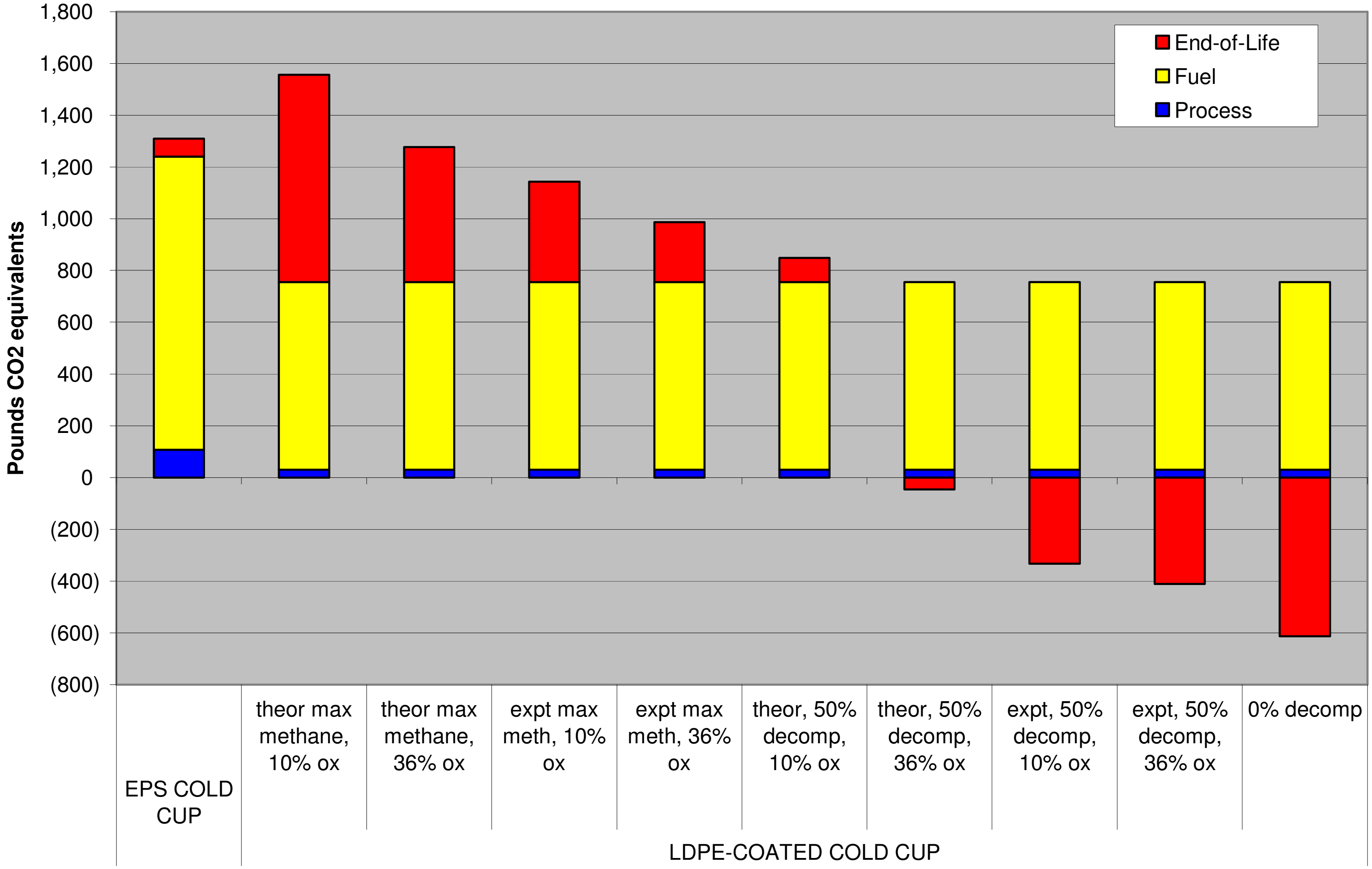


Figure 3-3a. Sensitivity Analysis on End-of-Life Greenhouse Gas for 9-inch Heavy Duty Plates (10,000 average weight plates)

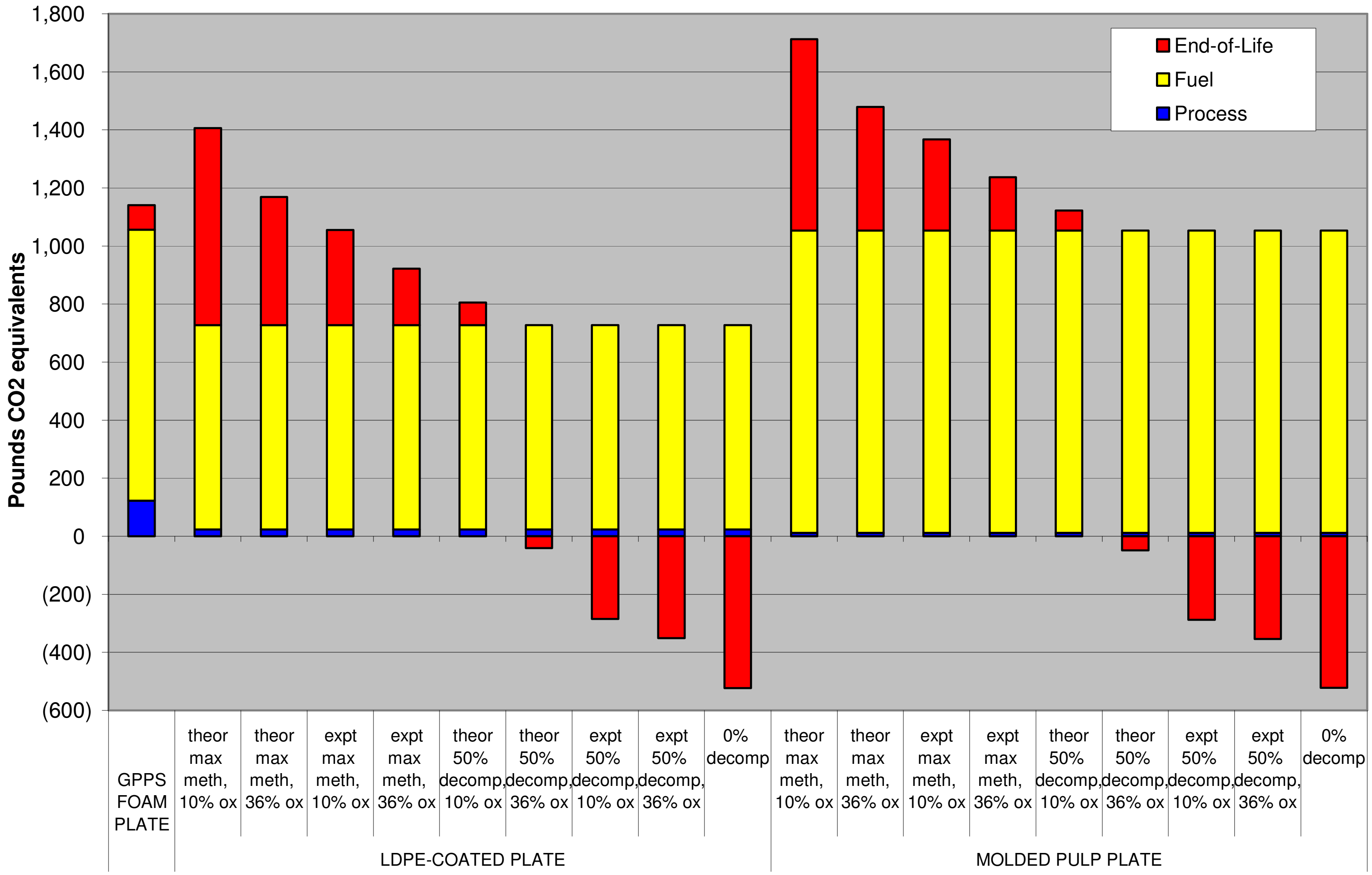


Figure 3-1b. Net Greenhouse Gas End-of-Life Sensitivity for 16-oz Hot Cups (10,000 average weight cups)

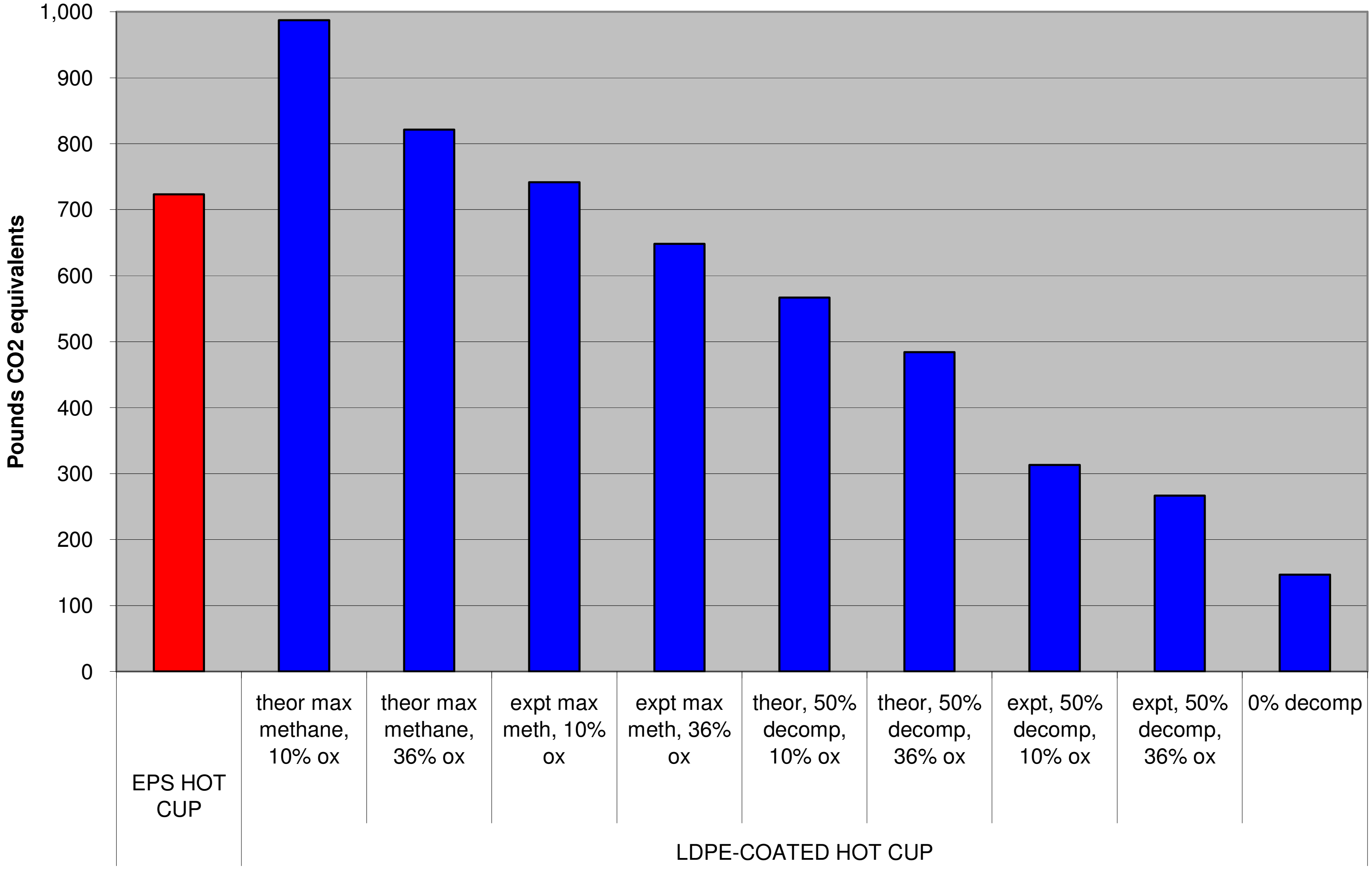


Figure 3-2b. Net Greenhouse Gas End-of-Life Sensitivity for 32-oz Cold Cups (10,000 average weight cups)

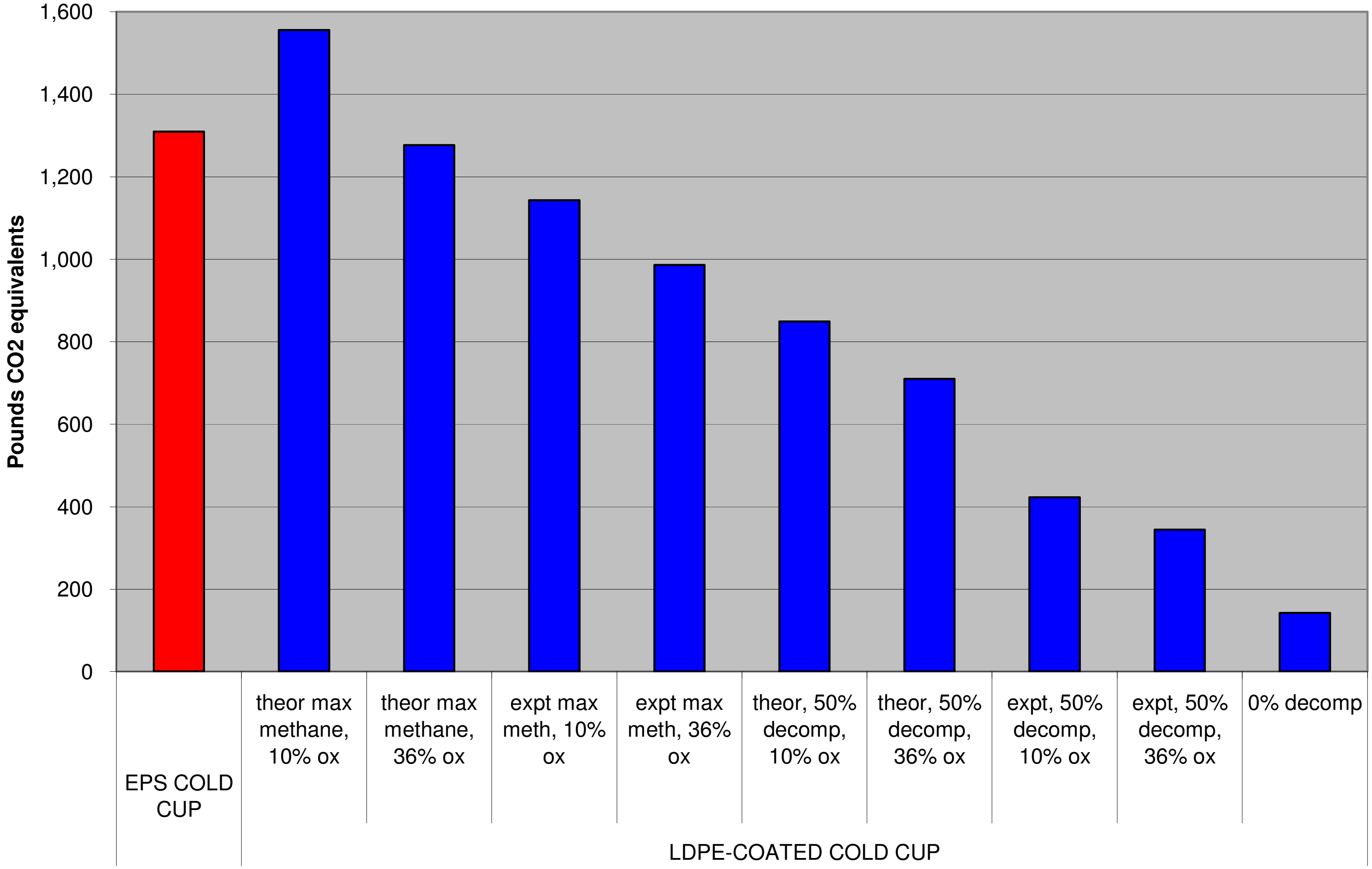
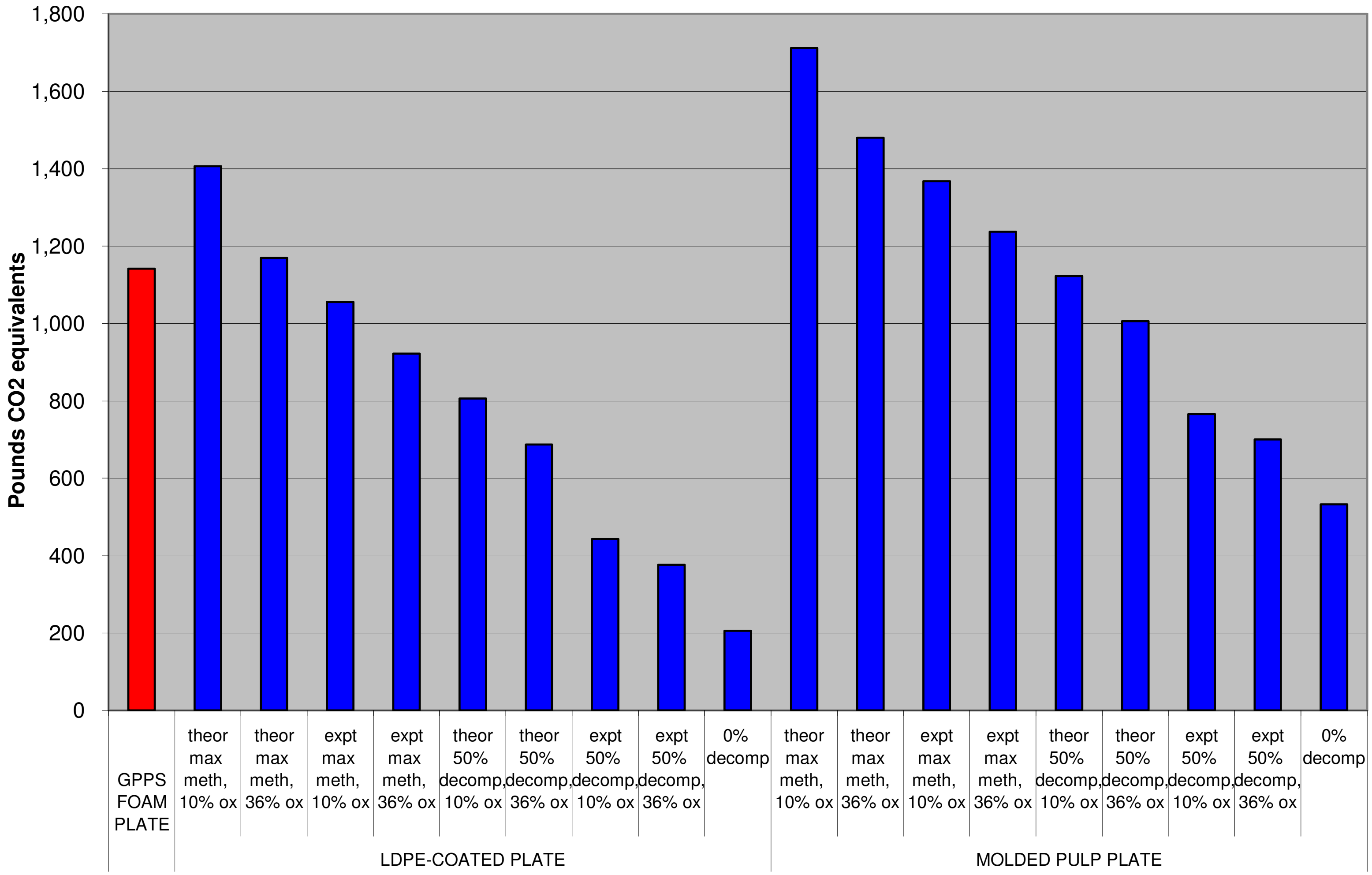


Figure 3-3b. Net Greenhouse Gas End-of-Life Sensitivity for 9-inch Heavy Duty Plates (10,000 average weight plates)



APPENDIX A

WATER USE

INTRODUCTION

Water use is becoming an increasing focus of attention in life cycle assessments; however, well-documented data on water use are currently hard to find because companies often do not track it. In this sense, a parallel can be drawn with carbon dioxide, which was not tracked by industry until global warming became an issue of concern. In fact, some of the emerging focus on water use can be attributed to concerns about the effect of global warming on water supplies. Because of the scarcity of reliable data on water use on a unit process basis, water use has not routinely been included in U.S. life cycle studies.

Fresh water is a limited resource throughout large parts of the world, and more attention has been paid to its use in recent years. According to the U.S. Geological Survey, U.S. water withdraws in the year 2000 totaled 408,000 Mgal/day. Of the total withdraws, 85 percent was freshwater; 76 percent of the freshwater withdraws were surface water, and 24 percent were groundwater.[35] Freshwater surface bodies of water are replenished by rainfall and melting snow; the latter tends to be a more consistent flow and ensures that rivers flow when no rain is falling. Unfortunately, rising global temperatures and the retreat of glaciers is threatening to disrupt the balance that currently exists. A shift in the mix of precipitation that falls as rain and as snow leads to increased runoff and flooding, and a reduced flow of water during dry months.[36]

Water withdraws and consumption in the U.S. have more than doubled since 1950, while the amount of water available per person has dropped 45 percent, from 18.6 thousand m^3/year per person in 1950 to an estimated 10.2 thousand m^3/year per person in 2000.[37] This average is ten times the level of 1,000 m^3/year per person that can be considered catastrophically low, yet it masks a large degree of variability within the U.S. Removing Alaska from consideration lowers the availability to 6.2 thousand m^3/year per person; the regions of the Lower Colorado, Rio Grande and California had respectively 0.3, 1.0 and 2.2 thousand m^3/year per person in 1990. Additionally, it has been estimated that about 20 percent of irrigated land in the U.S. draws on groundwater at rates that

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35 Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., and Maupin, M.A., Estimated use of water in the United States in 2000. U.S. Geological Survey Circular 1268, 2004.

36 Brown, L. How water scarcity will shape the new century. *Water Science and Technology*. Vol 23 No 4 p 17-22. 2001.

37 Izmailova, A.V. (2003). Water resources, water use and water availability in North America. In I.A. Shiklomanov & J.C. Rodda (Eds.), World Water Resources at the Beginning of the 21st Century. Cambridge University Press.

exceed replenishment.[38] Therefore, information on water consumption is important to consider when evaluating product systems so that decisions can be made to minimize water depletion.

Data from the USGS water use survey show that 82 percent of industrial withdraws are from surface water. Data for specific industries is unavailable, but trends can be seen on a state-by-state basis. Eastern and northern states and those with higher rainfall tend to use more surface-water, while dry western states use more groundwater.

This chapter describes the different categories for water use reporting and the sources of water use data for the production of foodservice products made from polystyrene foam, coated paperboard, and PLA.

SOURCES OF WATER

Surface Water

Approximately 81 percent of surface water withdraws in the U.S. are freshwater, consisting of water from rivers and lakes. Surface water that is withdrawn for industrial or thermoelectric cooling requires little or no treatment before it can be released back to the original source. One of the major concerns with cooling water is the temperature increase, which contributes to thermal pollution. Process water that needs to be treated on-site or at a publicly owned treatment works (POTW) is typically released back to a surface body of water.

Aside from cooling and process water that evaporates, agriculture is the largest consumer of surface water that will not be returned to its source. Fifty-eight percent of agriculture withdraws are from surface water, which represents 25 percent of surface water use and 20 percent of all water withdraws.[39]

Groundwater

Unlike surface water, which can be used and returned to its source, extracting groundwater is similar to using fossil fuel reserves. Aquifers are usually replenished at a very slow rate, and it is difficult to return water to the aquifers from which they were taken. Depletion of aquifers can have significant effects, including lowering the water table – which requires drilling deeper wells – and can result in land subsidence.[40]

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38 Shiklomanov I.A., Izmailova, A.V. (2003). Water management problems in North American: Canadian transfers. In I.A. Shiklomanov & J.C. Rodda (Eds.), World Water Resources at the Beginning of the 21st Century. Cambridge University Press.

39 USGS, 2004.

40 Konikow, L., and Kendy, E. Groundwater depletion: A global problem. *Hydrogeology Journal*. Vol 13 No 1 p 317-320. 2005.

Agriculture accounts for the largest percentage of groundwater use in the U.S. at 67 percent, followed by public supply at 19 percent and industrial uses at 4 percent.[41]

The effects of groundwater use are more complicated than simply reducing the amount of water available, because the quality of fresh water is just as important as its availability. Pumping water out of an aquifer lowers the pressure, which can allow infiltration of saline or otherwise degraded water from other sources.[42] While compromised groundwater can still be used for some purposes, it is unfit for drinking and most other uses.

TYPES OF WATER USE

As mentioned above, water can be used in many different ways. Some uses are consumptive (the water is not returned to the source from which it was withdrawn), and others are non-consumptive (e.g., cooling water that is withdrawn from a river and returned to the source after use). Generally, water use reported in LCA databases is reported in one of two categories: process and cooling. There is also some water use reported as "unspecified"; in this analysis, this is included with process water.

Cooling Water

Industrial processes frequently produce heat, which must either be transported to another process or released to the atmosphere. The high specific heat of water and its relative inexpensive availability make it an ideal candidate for heat transport. Cooling water can be released after a single pass through a system, or it can be cooled and recirculated. The use of evaporative cooling towers allows cooling water to be recirculated, lowering the total water withdrawn, but there are associated evaporative losses. Cooling water can also be recirculated in a closed-loop system using refrigerant to chill the water, minimizing water losses.

Process Water

Water use that is not specifically reported as used for transferring heat is generally classified as process water. Process water may include the following uses of water:

- Water that is consumed in chemical reactions
- Water that is incorporated into the final product (e.g., as moisture content)
- Water that is directly used in an industrial process and must be cleaned before it can be released;
- Water that is heated and used as steam;
- Water that is evaporated in industrial processes; and
- Water that is used for irrigation of crops.

41 USGS, 2004.
42 Konikow, L. 2005.

WATER USE DATA SOURCES

Life cycle inventories are constructed by assembling data sets for all the unit processes required to produce the functional unit of product output, beginning with raw material extraction and continuing through the entire sequence of processes required to produce the final output product. Data sets for individual processes are weighted according to the quantity of output from each process that is required to produce the final product.

The goal of this analysis was to identify water use for each unit process for each foodservice product and add the water use data to each unit process data set to construct a full life cycle model of water use for each product system. However, it was not possible to meet this goal. For most processes in this study, detailed information regarding process water in U.S. industries (quantity of water used, groundwater or surface water, salt water or freshwater) were not available. No comprehensive source of data on U.S. industrial processes could be found. Therefore, it was necessary to utilize other sources of data.

Data for a number of industrial chemicals and plastic resins were obtained from the Ecoprofile reports published by PlasticsEurope, which were done by Dr. Ian Boustead. The data in these reports are specific to manufacturing in Europe, including upstream processes such as thermoelectric power generation and petroleum refining. The data are presented in an aggregated manner, including not only the water use for the unit process of interest but also the aggregated total water use for all steps from raw material extraction leading up to that unit process. Without access to the weight factors used to develop the aggregated cradle-to-process output totals, it was not possible to determine the water use for individual unit processes.

For some industrial chemicals, data have been taken from Ecoinvent, a life cycle database with data primarily from European sources. Ecoinvent reports both unit process and life cycle water use for many processes. The sources of process water are listed individually (lake, river, ocean, well, etc.), but cooling water is not identified by water source. Some Ecoinvent data sets reported water designated as used for turbines (based on water used for European electricity generation). For these data sets, the turbine water use was replaced with U.S. data for average gallons of cooling water per kWh of electricity (see Electricity section below).

Although the *quantity* of water used for U.S. processes is expected to be similar to corresponding processes in Europe using similar process technologies, it should not be assumed that the *sources* of water will be the same in the U.S. and Europe. A number of different water sources are reported in the data sets in Ecoprofiles and in Ecoinvent, but because of geographical differences these are not assumed to be representative of water sources in the U.S. Therefore, water use data in this report are shown as total quantities without distinguishing the source of the water as coming from oceans, lakes, rivers, wells, etc.

While PlasticsEurope and Ecoinvent served as the primary data sources for water withdraws, a number of other sources were used. These include U.S. government publications such as the Farm Survey, the USGS Water Use report, an EPA Profile of the Pulp and Paper Industry, a DOE Profile of the Petroleum Industry and a paper by the DOE and the National Energy Technology Lab (NETL) on Fossil Energy and Water. The Environmental Defense Fund compiled several individual sources of water use in kraft pulp and paper manufacturing, and water use in the production of PLA came from a NatureWorks Ingeo™ data set published in the U.S. LCI Database in 2010.

Most sources did not distinguish between water use (withdraws) and consumption. Because data on water consumption was only available for a small number of unit processes, consumptive and non-consumptive use of water is not reported separately in this study.

Electricity

Thermoelectric power generation requires large amounts of cooling water for proper condensation. In thermoelectric generation, a fuel source provides heat to convert water into steam, which powers a generator. Cooling water is then used to condense the steam – usually in a shell and tube heat exchange system. Approximately 25 gallons of water are withdrawn for each kWh of electricity generated by this method, with one half of a gallon being consumed in evaporation.[43]

Two methods of water cooling are used in the U.S. in thermoelectric power plants – recirculating and once through. Once-through systems have higher total water usage (37.7 gal/kWh), but lower evaporation rates (0.1 gal/kWh); recirculating systems withdraw less water (1.2 gal/kWh), but a larger amount is evaporated (1.1 gal/kWh). Each has advantages and disadvantages according to the total amount of water available. In 2001 approximately 31 percent of units recirculated their cooling water.[44]

Approximately 92 percent of U.S. electricity is produced via thermoelectric generation, so this percentage is applied to the gallons of cooling water per thermoelectric kWh to estimate the overall gallons of cooling water per kWh of U.S. grid electricity.

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43 U.S. Department of Energy, NETL. *Addressing the Critical Link Between Fossil Energy and Water.* 2005.

44 Ibid.

Produced Water

When oil and natural gas are extracted from the ground, they come to the surface as a mixture of hydrocarbons, water, and suspended or dissolved solids. Because of this, the produced water can include a variety of contaminants, such as salts (dissolved solids) and hydrocarbons that need to be removed during cleaning. Cleaning costs range from less than one cent to several dollars per barrel, demonstrating the variety of conditions that produced water can be found in. The world average of produced water is two barrels for every barrel of oil; because wells in the U.S. tend to be older, the average in the U.S. is approximately 9.5 barrels of produced water for each barrel of oil. [45]

The majority of produced water (71 percent) is reinjected as water or steam to maintain reservoir pressure and increase oil production, although it can also be injected into the ground for disposal purposes. If it is clean enough, produced water can also be used for livestock and agriculture, or by industry. In areas where limited surface and ground water is available, it has the potential to be a valuable resource.

Currently, the majority of produced water is disposed of, either through injection or release to surface water. In the U.S., most water produced from onshore oil and natural gas wells is reinjected, whereas most offshore wells discharge to the ocean. While standards for discharge vary, this is the practice for offshore wells throughout the world.

Water Use in Polystyrene Foam Production

Water use data for the production of polystyrene and other plastic resins used as coatings on paperboard product were drawn from PlasticsEurope Ecoprofiles. While some U.S. water use data is available for the production of ethylene and pyrolysis gas, there are data gaps for U.S. water use data for other processes in the sequence of steps required to produce plastic resins. Therefore, the cradle-to-gate water use data in PlasticsEurope were used instead of using incomplete water use data for U.S. processes.

The PlasticsEurope resins data are fully aggregated; that is, they include water use for all upstream processes including the production of fuels and electricity. Because of the fully aggregated nature of the datasets, electricity-related water use could not be separated out, so it was not possible to adjust the cradle-to-resin data for differences in water use for U.S. and European electricity generation.

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[45] U.S. Department of Energy, NETL. *A White Paper Describing Produced Water from Production of Crude Oil, Natural Gas, and Coal Bed Methane*. 2004.

Water Use in PLA Production

Water use for PLA production was modeled using data published for NatureWorks Ingeo in the U.S. LCI Database. The Ingeo data include water used for corn irrigation, water used in corn wet milling processes (allocated among the wet mill coproducts), and water used in PLA production. Because the Ingeo cradle-to-PLA data set shows electricity as an input (rather than aggregating electricity production impacts into the cradle-to-PLA data set), water use for electricity production was added as described in the Electricity section of this chapter.

The corn irrigation water use published by NatureWorks is specific to the Nebraska and Iowa counties that supply corn to the Blair, Nebraska Ingeo plant. Not only is a low percentage of corn acreage in these counties irrigated (9.4 percent in 2000, compared to about 60 percent of all corn growing acreage in Nebraska), but the water use per irrigated acre for these counties (calculated by NatureWorks as 5 inches) is lower than the U.S. average water use per irrigated acre of corn in Nebraska (ranging from about 10 to 14 inches in 2003 and 2008 Farm and Ranch Irrigation Surveys). There is more rainfall in eastern Nebraska and western Iowa compared to other corn-growing regions of the Midwest.

Water Use in Paperboard Production

Pulp and paper production uses a large amount of water, in addition to the water needed to make the various chemicals used in the bleaching process. Water withdraws for the production of chemicals such chlorine dioxide, sodium hydroxide and oxygen came from PlasticsEurope and Ecoinvent; data sets evaluated for water use in pulp and paper mills came from Ecoinvent and a white paper by the Environmental Defense Fund.[46]

46 Environmental Defense Fund. White Paper No. 10A, Environmental Comparison – Manufacturing Technologies for Virgin and Recycled-Content Printing and Writing Paper. 1995.

APPENDIX B

PEER REVIEW

of

LIFE CYCLE INVENTORY OF FOAM POLYSTYRENE, PAPER-BASED, AND PLA FOODSERVICE PRODUCTS

Prepared for

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November 6, 2010

SUMMARY

At the request of The Plastic Foodservice Packaging Group, a peer review panel evaluated an expanded and updated life cycle inventory (LCI) of foodservice packaging; Franklin Associates (FAL) had originally completed the LCI in 2006 for the Polystyrene Foodservice Packaging Council, now known as The Plastic Foodservice Packaging Group (PFPG). The updated LCI examines the life cycle energy consumption, solid waste generation, greenhouse gas (GHG) emissions, and water use of 16 single-service containers across 4 categories: 16-ounce hot cups, 32-ounce cold cups, 9-inch high grade plates, and sandwich-size clamshells. The 2010 update extends the scope of the original study to include polylactic acid (PLA) containers, plus the analysis of water use.

In conformance with ISO 14044:2006 Section 6.3, the panel consisted of 3 external experts independent of the study. They reviewed the draft LCI report against the following six criteria, to ensure the analysis had been conducted in a manner consistent with ISO standards for LCI:

- 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 panel's detailed responses to each of the six questions are given below.

Is the methodology consistent with ISO 14040/14044?

In general, the study conforms to ISO standards. However, panel members noted the following:

- One requirement of ISO 14044:2006 is the clear definition of the study goal. According to Section 4.2.2 that goal "shall…unambiguously" state "the intended application; the reasons for carrying out the study; the intended audience…whether the results are intended to be used in comparative assertions intended to be disclosed to the public." FAL states that the study goal is "to provide PFPG with more complete information about the environmental burdens and greenhouse gas impacts from the life cycle of disposable foodservice products." (Page ES-1). The report also indicates, "A secondary intended use is public release of the study" (Page ES-2), in other words, making comparative assertions. Particularly in light of this second goal, critical assumptions should be very clearly stated in the Executive Summary—the only part of the report seen by many readers. As noted below, some of those critical assumptions need additional clarification and documentation.

Response: *Language has been added in several places in the Executive Summary to clarify the assumptions and limitations of the study. See responses to specific comments below.*

- ISO 14044:2006 further requires that a report with a "comparative assertion intended to be disclosed to the public" include "detailed sensitivity analyses in the life cycle interpretation phase" (Section 5.3.1). In compliance, the study includes a sensitivity analysis of landfill decomposition rates and their effect on GHG formation. However, since this study will be made public, sensitivity analyses for several other important assumptions should also be included.

  - At multiple points in the report, the study authors note that **product weight** has a significant impact on study findings. For example, on page ES-1, the authors state "Because this study is based primarily on average weight polystyrene foam and paperboard products from the original PSPC study, plus a limited number of PLA product samples, the results of this study should *not* be used to draw general conclusions about comparative results for the full range of product weights available in each product category". The authors note that they collected weights on multiple products, yet the Tables of product weights shown in the Executive Summary and on page 2-5 show only single values. The study would be improved if the authors reported a range of observed values for product weights (even if the analysis is based on a single weight) and if some sensitivity analyses related to product weight were performed.
    Response: *The intent of the project was to do a basic comparison of PLA products to the* ***average weight*** *products from the original PSPC report. Language has been added to the Goal and Scope sections of the report to clarify this. The range of products weights from the 2006 study has been added to the weight tables, and a link to the 2006 PSPC report has been added for readers interested in the full range of results from that report. Due to the difficulties in obtaining PLA product samples, it was necessary to make estimates of some PLA product weights; the basis for the estimates are described in the report text and weight tables. Wording has been added to the Conclusions section to clarify that the statements apply to the average weight products analyzed in this study.*

  - The authors note on page 2-60: "The **corn irrigation water use** included in the NatureWorks data set is specific to the Nebraska and Iowa counties that supply corn to the Blair, Nebraska Ingeo plant. Only 9.4 percent of the corn acreage in these counties is irrigated, compared to about 60 percent of all corn acreage in Nebraska. In addition, the water use per irrigated acre for these counties is lower than the average water use per irrigated corn acre, because there is more rainfall in eastern Nebraska and western Iowa compared to other corn-growing regions of the Midwest. The average amount of water applied per irrigated acre for the Blair plant's supplying counties was reported by NatureWorks as 127 mm (5 inches). In contrast, recent U.S. Department of Agriculture Farm and Ranch Irrigation Surveys reported averages of 14.4 inches of water per irrigated acre of Nebraska corn in 2003 and 9.6 inches of water per irrigated acre of Nebraska corn in 2008.

Different sourcing for the corn used for PLA could have a significant effect on the water use results." A sensitivity analysis is recommended that would examine a more typical water use pattern for corn production. In addition, it is not clear if the energy required for pumping irrigation water is included in the energy estimates.
Response: *Because the Blair, NE plant is the sole commercial PLA production facility in the U.S., it is reasonable to use irrigation data that represent the corn supply for that facility. It is noted on page 2-60 that "Different sourcing for the corn used for PLA could have a significant effect on the water use results." The NatureWorks PLA data set in the U.S. LCI Database used in this analysis is a cradle-to-resin data set that does not separately report energy use for individual life cycle steps. As the data module report states that the analysis includes inputs of electricity and fuel use on the farm and inputs of irrigation water, it is assumed that the energy for pumping irrigation water is included.*

- As noted on page 1-7, "Scrap from product fabrication is treated as a co-product if it is recycled, and treated as a waste if it is disposed. In other words, the foodservice product system carries no burdens for material inputs that end up as fabrication scrap that is recycled into some other product." It is a common practice to split burdens between the generating system and the system using the materials. A sensitivity analysis assessing a different **allocation method** would improve the study. In addition, it is noted on Page 1-7, "all corn growing impacts are assigned to the corn, and none to the corn stover (stalks and leaves) that are typically left in the field. The harvested corn is then processed at a corn wet mill, which produces coproducts of corn gluten feed, corn gluten meal, heavy steep water, and corn germ. As described in an LCA study using NatureWorks data mass-based coproduct allocation is used to divide the corn wet mill burdens among the outputs." Sensitivity analyses on choice of allocation methods would be useful here as well.
Response: *It is common practice to allocate burdens for* ***postconsumer*** *recycled material between the various systems in which the material is used as part of the finished product. However, in the case of* ***preconsumer*** *converting scrap, the material has not had a useful product life in the system generating the scrap. Therefore, all the material burdens are assigned to the system* ***using*** *the scrap, since this is the system in which the material first becomes part of a finished product delivered to consumers.*

  The PLA data set published in the U.S. LCI Database is an aggregated cradle-to-resin data set; therefore, it is not possible to conduct any alternative coproduct allocations on the wet mill.

- A zero **recycling rate** was assumed for all containers in this updated study. However, some foodservice container recycling programs already exist or are soon coming on-stream. PS single-serving containers can be collected through curbside programs in Ontario, Canada, where over 50% of households have access to blue box programs. Last year the Environmental Protection Agency in

Taiwan announced it would complete arrangements for a PLA recycling system in 2010. Plarco is piloting a process to convert post-consumer PLA containers back into lactic acid to be used in producing virgin PLA resin.
Response: *While there is some recycling of the types of foodservice products in this study, the levels are still low on a national basis. The 2006 PSPC report included analysis of composting and recycling of containers at 2 percent of generation. As stated in the Scope and Boundaries section, "The scope of this analysis does not include recycling or composting of any of the products studied." Language has been added to refer interested readers to the 2006 PSPC report.*

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

The objectives, boundaries, and scope chosen for the study seem appropriate. Panel members did express the following concerns and comments.

- The functional unit is defined as 10,000 disposable food service items. The study authors do include the insulating sleeve often applied to coated paper hot cups; however, they do not include the common practice of double cupping paper hot cups and doubling less stiff plates. Panel members want to be sure the items studied are equal in functionality. A reference is made to "a 2009 analysis of lighter-weight GPPS foam plates and poly-coated paperboard plates of equivalent strength" without defining equivalent strength. Because disposable foodservice plates can be quite flexible, confirmation is needed that the comparison for 9-inch plates would not include the user using double plates. Stiffness is probably more relevant.
  Response: *It is difficult to determine true functional equivalence of products within each category due to differences in the properties of the materials, variations in potential use applications, etc. For plates, two plates with different stiffnesses would provide equivalent functionality in applications in which the food served on the plate is below the maximum load limit for both plates. However, if the load of food is heavier than one of the plates can support, then that application would require two of the less stiff plate but only one of the stiffer plate. For the heavy-duty plates analyzed in the 2006 study, data on the stiffness of individual heavy-duty plates were not available. The results shown in the tables and figures for the average weight 2006 products are based on individual products, and the effects of double product use can easily be estimated by multiplying the single product results.*

  The 2009 plates represent a ***different*** *weight class of plates from the 2006 plates. For the two lighter weight plates from the 2009 study, the manufacturer of the PS foam plate provided strength information indicating that the 4.7 g GPPS foam plate and the 12.1 g coated paper plate had equivalent strength. The higher weight of material in a single coated paper plate provided equivalent stiffness to the lighter GPPS foam plate such that single plates had equivalent functionality on a one-to-one basis.*

- The boundaries do not include indirect land use for agricultural operations (Page 2-2). There is some controversy associated with the inclusion of indirect land use in life cycle inventories, since other indirect effects (e.g., indirect effects on petroleum markets of use of petroleum feedstocks for EPS production) are generally ignored in performing life cycle inventories. Nevertheless, in the United States, as part of the Renewable Fuel Standard (RFS), the U.S. Environmental Protection Agency has included indirect land use in comparisons between petroleum based fuels and fuels derived from biomass. This would seem to establish an important precedent for life cycle studies. The EPA results for greenhouse gas emission estimates for corn based fuels indicate that the domestic and international land use change associated with corn based fuels dominate the total greenhouse gas emissions. For this study, these potentially significant indirect land use emissions were ignored. At a minimum, the anticipated magnitude of the effect of this assumption should be noted in the Executive Summary of the report.

  http://www.epa.gov/otaq/fuels/renewablefuels/regulations.htm
  http://www.epa.gov/otaq/renewablefuels/420r10006.pdf
  http://www.epa.gov/otaq/renewablefuels/420f09024.pdf

Response: *Indirect land use change is defined as "the conversion of non-agricultural land to agricultural land as a consequence of changes in agricultural practice elsewhere" (PAS 2050). Indirect land use change was included in the RFS evaluation to account for potential consequences of land conversions in other locations when huge quantities of U.S. corn are diverted from current food-related uses in order to produce future target amounts of corn-derived fuel. There was much uncertainty about the types of crops that would be used to replace the corn diverted from food use to fuel use, where the crops would be grown, and the types of land that would be converted to agricultural use.*

Indirect land use is not typically included in product life cycle studies for several reasons. For PLA products, there could be indirect land use changes if the use of corn as a feedstock for PLA reduced the available U.S. corn supply such that non-agricultural land had to be converted to agricultural use to make up for this. However, it is unclear whether there have been indirect land use changes that can be attributed to the use of corn for PLA production. Additionally, there are large uncertainties in projecting the types and locations of land that might be converted to agricultural use as a result of using a given quantity of corn as feedstock for PLA. The greenhouse gas emissions for indirect land use change can vary widely depending on assumptions about the type and location of land converted. Furthermore, this analysis is an attributional LCI, not a consequential LCI. As such, the analysis is based on the environmental burdens attributed to the products being studied and does not attempt to model the consequential effects on other systems. A section on indirect land use change has been added to the System Components Not Included section of Chapter 2.

- The near-zero inherent energy burden of PLA comes at the expense of land use. Arable land is a limited resource, perhaps even more than fossil fuel. PLA does put the land use issue up front (where PE and PS have relatively little burdens) and introduces the agricultural use of water, which is significant and rendered unavailable as it soaks in/evaporates/undergoes transpiration. Panel members are glad to see this study includes at least a beginning discussion on water usage. Far more needs to be done on water usage definitions and conventions, possibly starting with cooling water vs. process water. The land use issues will also be the subject of much future life cycle methodology development.
  Agreed. No response required.

- Expanding the boundaries of this study to include both fossil fuel-based energy of material resource (EMR) and bio-based EMR from wood and corn grain use is good for the reader. For bio-based EMRs, the energy is tracked and reported separately, which is a good practice. As noted in the discussion of assumptions, the decision to include these energy flows has a significant impact on the conclusions from the study.
  No response required.

- The process boundary begins with agricultural activity or extraction and ultimately creates food service items of very similar service type. The study is expanded to include carbon dioxide equivalents (CO2E), generation for various landfilling and incineration end-of-life options for food service items.
  No response required.

- The geographical boundary specifying final production of materials in the USA that might be sourced world-wide is reasonable and appropriate.
  No response required.

- The study does not include the use step in the life cycle, which is acceptable if each food service item is expected to be used similarly.
  No response required.

- No secondary packaging was considered, although a discussion is included about the differences for sleeves of EPS vs. unfoamed food service items.
  Response: *For readers interested in the contribution of secondary packaging, language has been added directing the reader to the 2006 PSPC report, which did examine the contribution of packaging.*

- The inclusion of water usage is justified and appropriate. The division into process use and cooling use is appropriate as the effect on water quality will be different. Water is not consumed as is energy. Use of water can change its availability for other use in either quality or physical form or location.
  Agreed. No response required.

- Excluded system components are the typical list and are reasonable. Other methodological limitations are typical and reasonable or ranges of scenarios are included, such as for landfill degradation.
  No response required.

- In general, with the exceptions noted in this review, the allocation methods used in this study seemed reasonable.
  See responses to specific allocation comments.

- Franklin Associates is not using post-consumer recycled materials, pulp or plastic, for the foodservice items. In so declaring, they comply with ISO standards and inform the reader. Such a boundary definition is reasonable with respect to commercial foodservice items.
  No response required.

Are the assumptions used clearly identified and reasonable?

Overall, the assumptions in this study are reasonable and clearly identified. However, the Executive Summary should plainly state that the choices made for a number of study assumptions significantly impact conclusions that can be drawn from the study. These key assumptions involve:

- Product weight
- Inclusion of bio-based EMR
- Choice of whether solid waste is reported by volume or weight
- Greenhouse gas production by landfills
- Inclusion of indirect land use
- Corn irrigation practices
- Differentiation of water consumption and withdrawal
- Choice of allocation method.

Response: *Language has been added to the report as suggested.*

Product weight

Page ES-2 states, "For the most part, the products modeled in this analysis are based on the average weight products in the 2006 PSPC study." This assumption causes great concern. As time passes, technology changes; container manufacturers seek to reduce raw material cost through light-weighting. The study itself gives one of the best illustrations of this process for heavy duty 9-inch plates. The 2006 10.8-gram GPPS foam plate had been functionally replaced by a 4.7 gram plate in 2009. And, the equivalent strength LDPE-coated paperboard plate dropped from 18.4 to 12.1 grams over the same period. Why weren't 2010 samples of each product type taken to establish current container weights?

Response: *The 2009 plates do* **not** *replace the 2006 plates. The 2009 plates are for a different weight class of plate than the heavy-duty plates and should not be directly compared to the heavy-duty plates. Although the 2009 plates are in a different weight class from the heavy-duty plates from the 2006 study, results for the two lighter class plates are provided for two reasons: (1) to illustrate how LCI results can vary based on the weight of the product, and (2) to present a comparison based on actual equivalent strength (since strength data was not available for the heavy-duty plates). Text has been added to the report discussion, tables, and figures to clarify that the 2006 and 2009 plate results represent different weight classes of plates.*

Of even greater concern are the assumptions of "estimated" PLA container weights, since no PLA containers of the types studied currently exist. How reasonable are these estimates?

- The 32 oz cold cup weight estimates for PLA cups are done two ways. The first way looks at ratios of PLA and PP 24 oz cups weights and applies that ratio to a 32 oz PP cold cup. The note suggests the 24 oz PLA cups are 50% heavier than 24 oz PP cups. The density ratio is 1.38, suggesting the PLA cup is actually thicker than a PP. PLA exhibits a higher flexural modulus than PP, so a cup could be thinner and possess the same resistance to crushing. PLA is more brittle than PP and sensitive to elevated warehouse temperatures, which could result in a deliberately thicker PLA cup. Thus, the 50% heavier statement could represent an optimized container. This approach is generally valid. The second way says on page 2-4 that the relative densities for the PLA and PP plastics were applied to the 32 oz PP cup. This is taken to mean the density ratio. On Table ES-1 and Table 2-1 the second way is described as depending on ratios of PS and PLA clamshells. The note on the tables says 15% heavier while the ratio of PLA density to PS density is 1.17 and the reference material is unstated. There is a conflict in the text and table; the calculations and verbiage should be reviewed.
  Response: *The description in Tables ES-1 and 2-1 for the second estimate of 32 oz PLA cup weight was incorrect. The second estimate was based on the PP cup weight and the ratio of resin densities. However, the 26.8 g weight was incorrectly based on the weight of the 32 oz PP cup scaled using the weight ratio of PLA and <u>PS</u> products (1.25 g/cm3 for PLA, 1.05 g/cm3 for PS). When the 32 oz PP cup weight is multiplied by the ratio of PLA and <u>PP</u> densities (1.25 g/cm3 for PLA, 0.9 g/cm3 for PP), the weight of the 32 oz PLA cup estimated by the second method is 32.4 g instead of 26.8 g. This is much closer to the alternative estimate that is based on the weight ratios of 24 oz PP and PLA cup samples. The weight table and results tables and figures for this system have been updated throughout the report.*

- The 9 inch PLA plate weight is estimated, page 2-1, as the PS plate times the ratio of PS/PLA densities. The ratio of densities is 1.17, or PLA 17% heavier. The text on Table ES-1 and Table 2-1 says the ratio of clamshells with PLA 15% heavier. The correct words are needed and calculations confirmed.
  Response: *The description in Chapter 2 of estimating PLA plate weight based on resin density is incorrect. Although the ratio of PLA and PS resin densities is 1.19*

(1.25 g/cm3 for PLA, 1.05 g/cm3 for PS), the ratio of the weights of actual samples of identically sized PLA and PS clamshells was 1.15. The resin density scaling method assumes that the same amount of material is used in each product regardless of differences in resin properties, while the weights of actual product samples would reflect adjustments in the product design to take into account individual material properties. Therefore, the product weight scaling method is considered a better way to estimate weights of products with equivalent functionality. For example, as noted in the reviewer comments above regarding resin properties, a PLA product could be made thinner than a product made from another resin with a lower flexural modulus, so that the PLA product could be lighter than would be predicted based on the resin density ratio. Therefore, the ***product weight*** *ratio for PLA and PS clamshells was used as a scaling factor when estimating the weight of PLA plates. The description in Chapter 2 has been corrected.*

Inclusion of Bio-Based EMR

In most previous Life Cycle Inventories, FAL has assumed that the "energy of material resource" is confined to products made using oil and natural gas as raw materials, and that wood or other biomass used in manufacturing products has no "energy of material resource". In the 2006 study which this work extends, the peer review panel noted that this assumption could affect study findings. In this 2010 update to the 2006 study, EMR for bio-based resources have been tracked and the decision concerning whether to include these energies does impact study findings related to energy. This should be clearly highlighted in the Executive Summary.
Response: *Language has been added to the Executive Summary as suggested.*

Solid Waste Volume and Mass

The authors have indicated the differences in results associated with reporting solid waste in volume or mass units. This should be clearly emphasized in the Executive Summary.
Response: *Language has been added to the Executive Summary as suggested.*

How were the landfill compaction factors established for PLA?
Response: *The experimental landfill compaction density factors are from analyses of classes of products in municipal solid waste (paper, solid plastics, foam plastics, plastic film, etc.). The factors reflect the rigidity of the products and how samples of products compact under pressure and moisture conditions in landfills. Separate compaction factors were not available for products of different materials within each category. Therefore, the landfill compaction factor used for PLA products was the same compaction factor used for all solid plastic foodservice products in the analysis.*

Greenhouse gas production in landfills

Franklin Associates examined the impact of landfill decomposition of paper based as complete or not at all, based on published methodologies and results. This is proper. However, the assumption of equimolar anaerobic generation of carbon dioxide and

methane deserves explanation because of the impact of the presence of methane. The reference is needed, and basis (moles or mass) on page 1-16 for landfill gas assumptions.
Response: *Language and references have been added to the decomposition section as suggested.*

Page 2-43 states "The primary three atmospheric emissions reported in this analysis that contribute over 99.9 percent of the total CO_2 eq for each system are fossil fuel-derived carbon dioxide, methane, and nitrous oxide", which is inconsistent with the statement on page 2-54, "For the solid PLA systems, fossil carbon dioxide is also the largest contributor to the process and fuel-related CO_2 eq, but nitrous oxide emissions account for about 4 percent of the total. The nitrous oxide emissions are mainly associated with agricultural operations." It is surprising that agricultural N_2O emissions are this small. The report should indicate the assumptions made about the conversion of nitrogen fertilizer to N_2O.
Response: *It is not inconsistent to state that fossil CO_2, methane, and nitrous oxide together account for more than 99 percent of the total CO_2 eq for each system, with nitrous oxide contributing approximately 4 percent of the total CO_2 eq for solid PLA products.*

The nitrous oxide emissions for PLA ***resin*** *are based on process emissions of 0.37 g N_2O per kg of PLA resin, from the cradle-to-PLA data set in the U.S. LCI database. Because the data set is provided as a rolled-up data set, it is not possible to further examine the assumptions about N_2O emissions from nitrogen fertilizer. The total cradle-to-PLA* ***product*** *CO_2 equivalents include GHG emissions not only for agricultural operations but also for production and combustion of all process and transportation fuels used to produce PLA resin and convert it into finished products. Therefore, a 4 percent overall contribution from nitrous oxide does not seem unreasonable.*

FAL has indicated the differences in greenhouse gas emission results are associated with various levels of landfill methane production. This should be clearly emphasized in the Executive Summary.
Response: *Language has been added as suggested.*

Inclusion of Indirect Land Use

As noted in the comments on system boundaries, indirect land use can be a significant contributor to total greenhouse gas emissions. The authors should note in the Executive Summary that the choice of whether or not to include these emissions can significantly impact greenhouse gas emission results.
Response: *As described in a previous response, a discussion of indirect land use change has been added to the System Components Not Included section of Chapter 2. Exclusion of indirect land use change has also been noted in the Observations and Conclusions section of the Executive Summary.*

Differentiation among Water Use, Consumption, and Withdrawal

The authors note on page A-5, "Most sources did not distinguish or define water use, withdraws, and consumption. Because data on water consumption was only available for a small number of unit processes, consumptive and non-consumptive use of water is not reported separately in this study." The Appendix is where the distinction between water consumption and withdrawal is noted. "Water use" is the term employed in the rest of the document. The distinction among use, consumption, and withdrawal needs to be made clearer throughout the document, and particularly for cooling water use and irrigation, some indication of whether consumption or withdrawal is being documented needs to be specified.
Response: *Data sources did not distinguish between consumptive use of cooling water and non-consumptive (recirculating) use of cooling water, so it was not possible to report separately. Language has been added to the report to clarify this.*

Are the sources of data clearly identified and representative?

The sources of data are clearly identified. Panel members offered the following comments and concerns about them:

- In paragraph 4, Page ES-1 states, "…this study is based primarily on average weight polystyrene foam and paperboard products from the original PSPC study…" The product weights assumed probably have the single greatest impact on the study results. Page ES-19 explains, "Material production burdens for a product are calculated as the product of the burdens per pound of material multiplied by the pounds of material used in the product system. Many grades and weights of disposable foodservice products are available in the marketplace." How was the "average" weight developed? Was a sampling plan developed? From how many manufacturers were samples collected? How many samples were collected per manufacturer? At the very least table ES-1 should include this information.
Response: *As noted in responses to earlier comments, language has been added to the report to clarify (1) that this analysis is based on the average weight products from the 2006 study and (2) that the scope of the study did not include updating the weights of the full range of product weights available in these product categories. The reader is referred to the publicly available 2006 PSPC report for results covering the full range of sample weights collected for the original project.*

- The treatment of secondary packaging needs clarification. Secondary packaging was included in the original report, but not in this modification. Some further explanation for this is needed.
Response: *As noted in the last paragraph of the Scope and Boundaries section, "The focus of this analysis is on the differences in environmental profiles for the products themselves. Secondary packaging is not included." Language has been added referring interested readers to the 2006 PSPC study.*

- On page ES-6 report contains the following: "The *net* energy consumption for each system is calculated as the process and transportation energy minus the energy content in landfilled products minus the energy recovered at end of life from combustion of products and combustion of recovered landfill gas from decomposition of landfilled products." The energy content of the manufactured product needs to be included in the definition. It appears the calculations have included the "energy content of manufactured products".
Response: *The description has been corrected.*

- Why were the global warming potentials from the second IPCC assessments used, rather than the most recent (Page ES-13)?
Response: *Although two subsequent updates of the IPCC report with slightly different GWPs have been published since the second assessment report (SAR), the GWPs from the SAR are used for consistency with international reporting standards. The United Nations Framework Convention on Climate Change reporting guidelines for national inventories continue to use GWPs from the SAR. For this reason, the U.S. EPA also uses GWPs from the IPCC SAR, as described in the Executive Summary of the U.S. EPA* **Inventory of U.S. Greenhouse Gas Emissions and Sinks.** *Explanation has been added to the report.*

- Page 1-12 states, "Taking into consideration budget considerations and limited industry participation, the data used in this report are believed to be the best that can be currently obtained." How did "budget considerations" and "limited industry participation" affect the scope of the data collection?
Response: *This project was scoped as an extension of the 2006 study, not as a complete update. Therefore, the scope of work did not include an extensive sample collection program similar to the sample collection done for the 2006 study. In cases where we were aware of more recent analyses conducted for manufacturers of certain products, Franklin did request permission from those manufacturers to use more recent data on their products; however, not all manufacturers opted to participate.*

- Franklin Associates cites Natureworks LCI in the US LCI Database. That study states that the corn used for PLA comes from established fields close to Blair, Nebraska. The consequences of land clearing to grow the corn are assumed not relevant. While this is true for the particular case of PLA from Natureworks, production in other localities could have other land use assumptions. Franklin Associates needs to more explicitly state the PLA data, particularly land use and water use, come from the US LCI Database and the details are not subject to their scrutiny.
Response: *Language has been added to the report to note that the PLA data in the U.S. LCI Database are provided as a rolled-up cradle-to-resin data set, which does not allow further evaluation of the flows for individual subprocesses. Although Franklin Associates did not have access to all the underlying data and assumptions for the PLA data set, it should be noted that the PLA data were peer reviewed by Dr. Ian Boustead, so the PLA land use and water use modeling have been closely scrutinized by an experienced LCA practitioner. Furthermore, using information provided by Dr. Erwin Vink and USDA records, Franklin staff were able to confirm*

the calculations of irrigation water use for the corn supply chain specific to the Blair PLA plant.

- One objective was to use publicly available information when possible for the study. Data sources and methodology sources are clearly identified and publicly available for PLA and for end-of-life investigations and for the pulp and for the polyethylene and for the polystyrene. Private sources are noted, correctly.
  No response required.

- Proprietary data sources are also cited, such as for water. As Franklin Associates notes, there are few standards in water usage data. Franklin correctly notes that the water data are uncertain; based on literature results; lack details per unit operation, definition, and methodology; and should be regarded with caution when making conclusions.
  No response required.

Is the report complete, consistent, and transparent?

Overall, the report is generally complete and consistent in its breadth of subject and detail. It is recognized that much data are taken from other sources and those sources may be inconsistent in data collection and presentation. While the actual calculations are not transparent, the reader is generally not interested in those calculations and relies on the analyst to conduct such calculations properly. A check of values shows correct calculations.

Are the conclusions appropriate based on the data and analysis?

In general, the findings are appropriate based on the data, assumptions and analyses, with the following exceptions:

- Page ES-1 states a study goal was to extend the 2006 scope to include "…available PLA products corresponding as closely as possible to…the original LCI". Yet some of the PLA containers studied don't even exist, but are "estimated" based on assumptions about similar PS containers. Yet, to the knowledge of the panel members, PLA has not been foamed commercially. And, these "estimated" PLA containers were developed without input from the primary PLA resin producer NatureWorks. Drawing conclusions about containers which don't exist is of serious concern to at least one panel member.
  Response: *Since commercially available foamed PLA products could not be found, the PLA product results in the report are based on* **solid** *PLA products, which are available in the product categories of cold cups, clamshells, and other rigid food containers. Hot cups are not made of solid PLA; therefore PLA-coated paper hot cups are modeled, using actual product weights. Language has been added to the report to clarify that the PLA cold cups, plates, and clamshells are modeled as solid PLA, not foam PLA.*

- In paragraph 4, Page ES-1 states, "Because this study is based primarily on average weight polystyrene foam and paperboard products from the original PSPC study, plus a limited number of PLA product samples, the results of this study should *not* be used to draw general conclusions about comparative results for the full range of product weights available in each product category." However, isn't that what's being done with the conclusions for solid waste on page ES-20 and water use on page ES-21?
  Response: *Language has been added to the Key Observations and Conclusions section to more explicitly state that the conclusions apply to the product weights used in this analysis. See also response to following comment.*

- The importance of comparing LCI results in the context of uncertainty has been well accepted in recent years. However, though this LCI makes reference to uncertainty, it presents results as point rather than range estimates. For example, the study concludes that "…the total energy requirements for PS foam products are generally lower than…(heavier) PLA or paperboard products…" How does "generally" relate to "significantly"?
  Response: *In the Observations and Conclusions section, the term "generally" is used to refer to trends across all four product categories, based on the differences that are considered significant in individual product comparisons within each product category. Significant differences between individual products within each product category are discussed in the results sections of the report. The wording in the Observations and Conclusions section has been clarified in the report.*

- Typically, FAL has assumed 10% uncertainty for energy data compared to 25% for air emissions. Yet this study repeatedly caveats the high degree of uncertainty in the water use data. What is FAL's percent estimate of uncertainty in the water results? Also, page ES-20 states, "The end-of-life greenhouse gas results presented here should be considered more uncertain than other emissions data." If FAL typically assumes a 25% uncertainty in emissions data, what is the uncertainty of the GHG data?
  Response: *Because we do not have access to the underlying data used to develop the majority of the cradle-to-gate process and cooling water use, we do not have a basis for estimating the uncertainty of the water results.*

  For GHG data, the majority of the ***process and fuel-related*** *GHG emissions are associated with fuel combustion. Since the fuel-related emissions are directly related to energy use, the uncertainty of the total process and fuel-related GHG emissions would be closer to the uncertainty of the energy data (10%) than the uncertainty for process emissions (25%). Because* ***end-of-life*** *GHG emissions depend on many assumptions (e.g, degree of decomposition of the material in the landfill, capture rate of methane generated, management of captured methane, etc.), they have much higher uncertainty and are thus reported separately from the process and fuel-related emissions.*

- As outlined in the "Assumptions" section, the conclusions associated with energy, solid waste, water use and greenhouse gases are all sensitive to the assumptions made in the study. This needs to be clearly communicated in the Executive Summary.
  Response: *Language has been added to the report as suggested.*

Additional Comments

- Obviously, water used for growing corn is counted in PLA's life cycle water use total. By what convention is the water used to grow trees for paperboard handled?
  Response: *For paperboard, the water use reported in the model is for converting wood inputs into paperboard at the mill. The modeling did not include any irrigation water use for growing trees. Data sets recently added to the U.S. LCI Database show some water use for growing tree seedlings in greenhouses; however, no water use was reported for subsequent forestry operations.*

- Including a copy of the 2006 study peer review panel's report would be helpful to the reader of this latest report.
  Response: *The report contains references to the peer-reviewed 2006 report, including a link to the peer-reviewed final report posted at ACC's website.*

- The difference between EPS and foamed GPPS needs to be explained. Otherwise, one definition should be used. Both terms are used on tables, figures, and in text.
  Response: *A description has been added to the Systems Studied section in Chapter 2.*

- While the important role of NatureWorks is explained in the report body, without additional information some readers may not understand its importance in the page ES-4 reference.
  Response: *Additional information has been added to describe NatureWorks as the sole commercial producer of PLA in the U.S.*

- The inclusion of the "Abbreviations" section on page vii at the start of the report is very helpful to the reader.
  No response required.

- Figure 1-1 also needs to include water inputs.
  Response: *Water inputs have been added to the figure as suggested.*

- Page 1-7 notes, "At least one manufacturer uses recycled industrial scrap as the material feedstock for molded pulp plate production; however, data from this producer were not available for this analysis." To understand the true range of product weights, shouldn't this data have been sought and included? Why was the data not available?
  Response: *The plate samples used to develop the molded pulp plate average weight include samples of this manufacturer's product that were purchased for the 2006 study. The manufacturer was contacted but elected not to provide plate manufacturing data for this study.*

- Page 2-42 refers to "International Panel on Climate Change (IPCC)" This should be the "Intergovernmental Panel".
  Response: *Reference has been corrected as suggested.*

- The charts with negative elements (energy and greenhouse gas emissions) should have a net value provided on the chart for each food service item, as provided in tables in Chapter 2. This would be especially useful in the Executive Summary.
  Response: *Net values have been added to the energy and greenhouse gas emissions figures in the Executive Summary, as suggested. Values were not added to the corresponding figures in Chapter 2, since Chapter 2 has separate figures showing net results.*

- Table 2-1 and Table ES-1, cold cups should say "32 oz PLA cup estimated XX% heavier than commercial PP cup". The same applies to plates.
  Response: *Footnotes have been added to the table to more clearly explain how PLA product weights were estimated.*

- Coloring some PS bars red and others blue needs explanation, or color all blue, Figures 2-1b, et al.
  Response: *In the net energy and net GHG figures, red is used for the PS bars to make them more readily identifiable.*

- On page 2-60 the report should note that cooling water can be once through, such as for some electricity generation, or recirculated through cooling towers or chillers. In the latter case, the water consumption should be that taken from the environment and not that circulated in manufacturing equipment per unit of production. Due to the uncertainty of definition of cooling water in literature references, the uncertainty of water withdrawn from the environment can be very large.
  Response: *Cooling water use is generally reported without clearly indicating whether it is once through or recirculated. It is agreed that the lack of detail about cooling water use as is a major contributor to the uncertainty in attempting to estimate water withdrawals from nature. Language has been added as suggested.*