Life Cycle Assessment of Polyethylene Terephthalate (PET) Beverage Bottles Consumed in the State of California

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Contractor's Report
Produced Under Contract By:
Brandon Kuczenski
Roland Geyer
Donald Bren School of Environmental Science and Management
UC Santa Barbara

STATE OF CALIFORNIA

Edmund G. Brown Jr.
Governor

Matt Rodriquez
Secretary, California Environmental Protection Agency

DEPARTMENT OF RESOURCES RECYCLING AND RECOVERY

Caroll Mortensen
Director

Department of Resources Recycling and Recovery
Public Affairs Office
1001 I Street (MS 22-B)
P.O. Box 4025
Sacramento, CA 95812-4025
www.calrecycle.ca.gov/Publications/
1-800-RECYCLE (California only) or (916) 341-6300

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Executive Summary

We present a life cycle assessment (LCA) of beverages packaged in disposable polyethylene terephthalate (PET) bottles delivered to California consumers. Our goals were to estimate the resource requirements and environmental impacts of the PET bottle product system in 2009, focusing on the contributions of post-consumer stages, and to evaluate a hypothetical materials recovery scenario in which bottles are reclaimed and used within the state of California.

Product System Description

* We estimate the California-average PET market to be 60 percent bottled water, 16 percent carbonated soft drinks, and 24 percent juice / sports / other drinks.

* On average, 1 kg of polymer contains 961 g primary resin and 39 g secondary (recycled) resin. 1 kg of polymer will package 27.9 liters of California-average beverage; 38.2 liters of bottled water; 24.2 liters of carbonated soft drink; or 19.6 liters of juice / sports / other drinks.

* PET bottles come with caps and labels made of polypropylene (PP). About 5 g of PP are used per liter of beverage.

* Our model does not include production of the liquid beverage, secondary packaging, resin additives, or impacts from retail and marketing.

Functional Unit and Reference Flows

* Our functional unit is delivery of beverages packaged in single-use bottles made from 1 kg PET resin to California consumers. Our model is designed to represent beverages included in California's CRV program.

* We report two different reference flows: (1) the demand for PET resin input to the beverage production stage, including both primary and secondary PET, and (2) the volume of beverage delivered to a customer.

Scenarios Modeled

* The primary product system, referred to as the **2009 Baseline** scenario, is parameterized as follows:
    - **27.9 L** contained per 1 kg of polymer;
    - **73 percent** collection rate;
    - **3.9 percent** recycled content;
    - **75 percent** of post-consumer PET exported.
    - **8 percent** of post-consumer PET reclaimed in California.

* We model two variants of the 2009 baseline: bottled water and carbonated soft drinks. We

describe these scenarios on a volume of beverage basis.

* We also model an alternative **California** scenario describing a hypothetical bottle produced and recycled in-state, containing 15 percent recycled content. This scenario is parameterized as follows:

    - **27.9 L** contained per 1 kg of polymer;
    - **73 percent** collection rate;
    - **15 percent** recycled content;
    - **100 percent** of post-consumer PET reclaimed in California.
    - PET not used in bottles is assumed to be used in food packaging applications in-state.

Results

* Use of 1 kg polymer in the baseline scenario (containing 3.9 percent recycled content) has a primary energy demand of **119.6 MJ**, requires **20,500 kg·km** of freight services, generates **0.727 kg** of solid waste and **0.547 kg** of secondary PET that is open-loop recycled. Figure ES-1 shows a detail of primary energy demand by life cycle stage.

* The baseline scenario leads to **5.79 kg CO_2-eq** of global warming potential, **57.5 g SO^2-eq** of acidification potential, and **10.9 g P-eq** of eutrophication potential (CML indicators). For a full listing of other impact indicators, see Chapter 4.

* In the California Alternative scenario, 1 kg polymer (15 percent recycled content) has a primary energy demand of **109.7 MJ**, requires **13,500 kg·km** of freight services, generates **0.715 kg** of solid waste and **0.437 kg** of secondary PET that is open-loop recycled.

* The alternative scenario leads to **5.31 kg CO_2-eq** of global warming potential, **52.3 g SO2-eq** of acidification potential, and **10.4 g P-eq** of eutrophication potential. Most of the reduction in environmental impacts is attributable to the increase in recycled content.

* On a volume of beverage basis, 1 L of California-average beverage generates a primary energy demand of **4.29 MJ** (or **3.94 MJ** in the alternate scenario). 1 L of bottled water requires **3.22 MJ** of primary energy. 1 L of carbonated soft drink requires **4.80 MJ** of primary energy.

Analysis and Interpretation

* The majority of environmental impacts in many impact categories, including global warming, acidification, and air pollution come from energy-intensive pre-consumer stages.

* Exceptions to the above can be found in eutrophication, which is dominated by post-consumer stages; ozone layer depletion, which is distributed throughout the life cycle; and several toxicity categories.

* Materials recovery makes a small contribution to environmental impacts in general. This stage includes the operation of recycling centers, curbside collection, and materials recovery facilities (MRFs), as well as consumer travel to drop-off locations. Consumer travel is the most energy-intensive part of the materials recovery stage, though this is highly dependent on the allocation method used.

* Freight services account for about 12 percent of primary energy demand, or about 30 percent of delivered energy (excludes feedstock and conversion losses). Demands for freight services are fairly evenly distributed among polymer production, beverage manufacturing, and reclamation life cycle stages.

* The baseline scenario creates 0.549 kg of secondary PET for each 1 kg of PET resin used. This material is not necessarily used in a manner that would displace primary production. However, if this material were to fully displace an equal amount of primary polymer, it would avoid **36.5 MJ** of primary energy demand (30 percent of the product system total) and **1.39 kg CO_2-eq** of global warming potential (24 percent of the total).

* Toxicity results are inconclusive because the inventory data used was found to be unreliable. Further study is necessary to determine toxicity impacts of the product system.

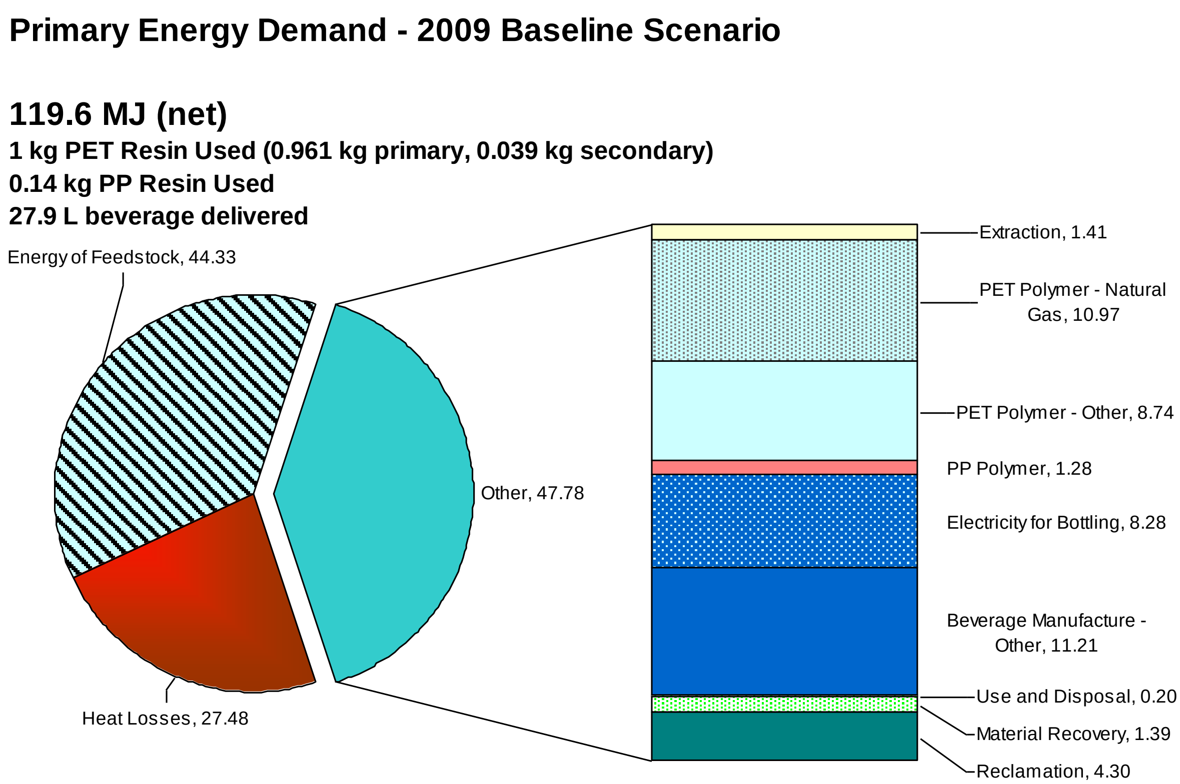

Figure ES-1 Primary Energy Demand generated by the consumption of 1 kg PET resin to produce bottled beverages.

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2 Extended Summary

The purpose of this report is to quantify the resource requirements and environmental impacts of beverages contained in recyclable single-use packaging made of polyethylene terephthalate (PET). PET bottles are the most-recycled plastic products in the U.S., thanks in part to container deposit programs such as California's CRV program. Approximately 73 percent of PET bottles sold in California in 2009 were returned for recycling (recycling collection rate), amounting to some 190,000 metric tons of plastic. This report is intended to be used as a baseline for comparison of the established PET bottle system against potential substitute product systems made of biopolymers.

This report uses life cycle assessment (LCA) to estimate the environmental impacts of the plastic bottle product system and to evaluate the environmental benefits that result from recycling. The focus of our report is on the end-of-life management of plastic bottles. We describe the impacts of post-consumer recovery in comparison to the entire life cycle and estimate the amount of secondary material that results from recycling. In addition to a baseline scenario which describes 2009 average conditions, we model an alternative scenario in which all post-consumer steps occur within the state of California.

2.1 Methodology

In our model, we apply process-based LCA techniques in accordance with international standards. We model the plastic bottle life cycle as a sequence of processes which transform inputs (e.g. plastic resin) into outputs (e.g. a bottle) while consuming energy and resources and releasing emissions into the environment. By summing the resource requirements and emissions across all processes, we estimate the total life cycle impacts associated with the product system from "cradle to grave."

We model the bottle's life cycle as consisting of the following stages:

- Extraction of raw material feedstocks;
- Production of primary polymer resins;
- Beverage bottle manufacture and beverage distribution;
- Use and disposal;
- Material recovery; and
- Reclamation of secondary material from post-consumer bottles.

For each stage we report a number of inventory indicators, which describe the resource requirements of the product system. These include different measures of demand for energy, freight services, and waste disposal. We also report a number of impact indicators, which represent estimates of potential environmental impacts that may result from the product system. These include global warming potential, acidification potential, and numerous others.

2.2 Product System Description

The PET bottle is produced through injection stretch blow molding of PET solid-state resin.

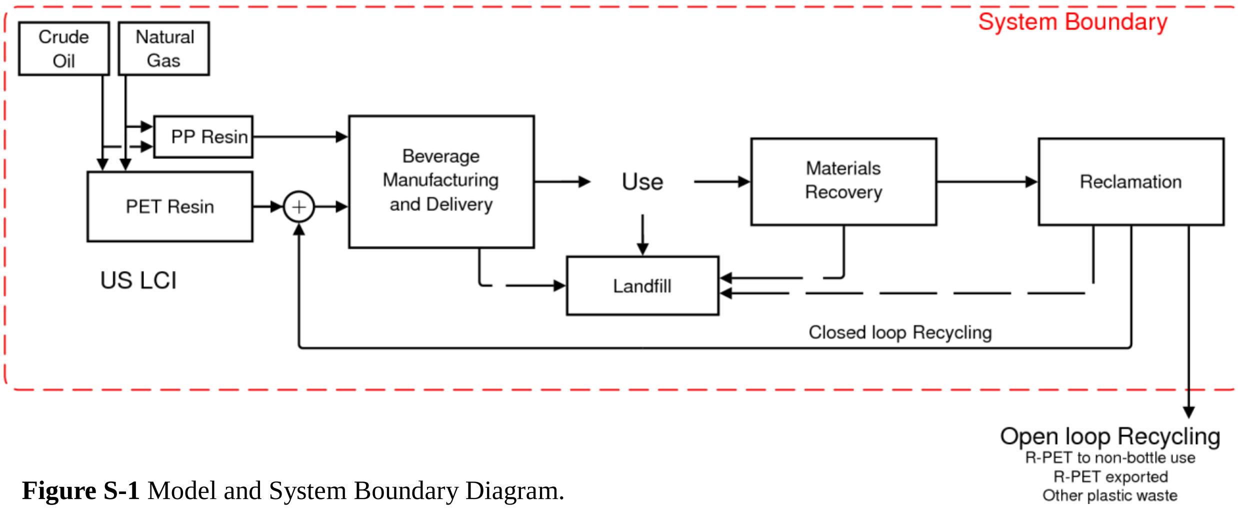


Figure S-1 Model and System Boundary Diagram.

A typical bottle weighs between 10 and 30 grams and contains around 0.5 L of fluid, depending on the particular beverage product. We model the California beverage market as comprising 60 percent bottled still water, 16 percent carbonated soft drinks, and 24 percent juices, sports drinks, and other refreshment beverages, based on market statistics reported in trade magazines. Under these assumptions (called the California-average beverage product), 1 kg of polyethylene terephthalate (PET) resin is sufficient to contain 27.9 L of beverage (about 36 g PET per L). Bottles are assumed to be outfitted with caps and labels made of polypropylene (PP). The California-average product requires 0.14 kg of PP per kg of PET (around 5 g PP per L).

No primary PP or PET resin is produced in California. All resin is assumed to be transported overland from domestic primary resin producers in the Eastern U.S. Bottles are assumed to contain 3.9 percent recycled content on average (i.e. 3.9 percent of the weight of PET in an average bottle is made up of secondary material) (NAPCOR, 2010). Bottles are assumed to be produced and filled at the same facility, and subsequently distributed to consumers. The post-consumer collection system is modeled based on statistics provided by CalRecycle. For 2009, the post-consumer collection rate was 73 percent (i.e. 73 percent of bottles were recycled, and the remaining 27 percent were landfilled). The percentage of recycled bottles is assumed to be returned to drop-off facilities for CRV redemption, and 24 percent of bottles are recycled in curbside programs, as indicated by CalRecycle statistics. Bottle recycling is a three-step process comprising collection, processing, and reclamation. Collection and processing are assumed to occur within California. The output of the processing stage is a sorted, compressed bale of bottles weighing roughly 500 kg.

2.3 System Boundary

Our model, shown in Figure S-1, includes processes directly involved in extraction of fossil fuels, polymer resin production, beverage manufacture, disposal of waste to landfill, materials recovery, and reclamation. The system boundary includes the production of fuel and electrical power, combustion, and transportation. Our model uses data from the U.S. Life Cycle Inventory database, supplemented with process data from Ecoinvent and PE International to fill data gaps. Ecoinvent processes were used to model landfills, incineration, supplies, and chemicals. PE

International processes were used for water and wastewater treatment.

We omit processes associated with producing the beverage, additives included in the resin, secondary packaging, retail, and marketing. Excluded from the modeling methodology are capital equipment, facility and administrative overhead, infrastructure, land use, and water use.

2.4 Scenarios

We present one baseline scenario representing California-average conditions for the year 2009 (2009 Baseline), and one alternative scenario (California Scenario) (summarized in Table S-1). The baseline scenario describes the use of 1 kg of polyethylene terephthalate (PET) resin (comprising 0.961 kg primary resin and 0.039 kg secondary resin) and 0.143 kg of polypropylene (PP) to package 27.9 L of California-average beverage. We also report two variants to the baseline scenario. In the BW variant, 26.2 kg of PET and 4.03 kg of PP are used to contain 1,000 L of bottled water. In the CSD variant, 41.4 kg of PET and 4.94 kg of PP are used to contain 1,000 L of carbonated soft drinks. Sports / juice / other drinks are not presented separately, but in our model, 51.0 kg of PET and 7.43 kg of PP would be required to contain 1,000 L. Post-consumer recovery and reclamation are modeled to approximate real-world conditions in 2009, in which the bulk of post-consumer bottles are exported to Asia via ocean freight.

The alternate scenario, denoted CA, is intended to describe the potential reduction in environmental impacts that could occur if reclamation and utilization of secondary material were improved in California. In this scenario, we model a hypothetical bottle produced in a California facility with 15 percent recycled content—1 kg of PET resin is assumed to contain 0.850 kg primary resin and 0.150 kg secondary resin. All post-consumer recovery and reclamation occurs within California, and no postconsumer bottles are assumed exported to Asia or shipped by freight to reclaimers on the East coast. The portion of secondary PET not used in bottles is assumed to find beneficial use in non-bottle food packaging within California.

Table S-1 Description of the scenarios modeled in the study.

	2009 Baseline	**California Scenario**	**2009 - BW Variant**	**2009 - CSD Variant**
Scenario Description:	2009 Collection statistics	15% Recycled Content / CA End-of-Life	Bottled Water	Carbonated Soft Drinks
Total weight of PET Resin [kg]: (Reference flow A)	1.00	1.00	26.18	41.35
Weight of secondary PET [kg]: (closed-loop recycling)	0.039	0.150	1.02	1.61
PET Recycled Content:	3.9%	15%	3.9%	3.9%
Weight of PP [kg]:	0.143	0.143	4.03	4.94
Contained Volume [L]: (Reference flow B)	27.9	27.9	1,000	1,000

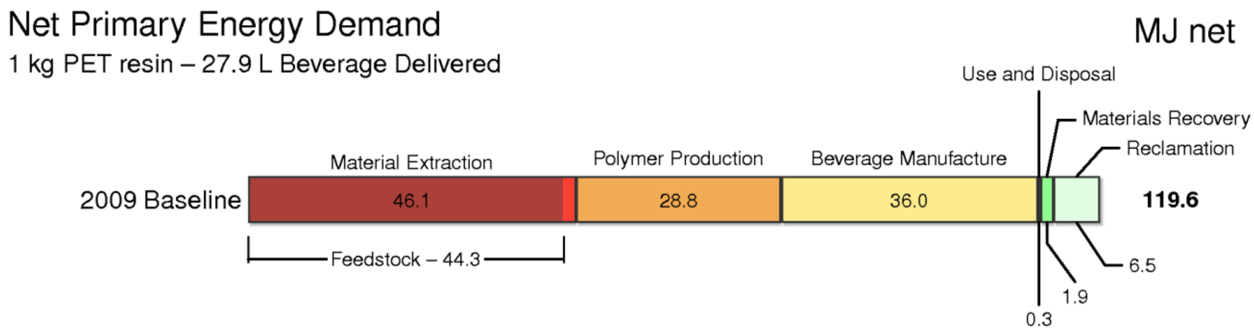


Figure S-2 Net Primary Energy Demand for 1 kg PET resin used in the product system, reported by life cycle stage. Feedstock energy is the energy content of oil and gas contained in the polymer.

2.5 Results

Our results are presented in terms of inventory (resource requirement) and impact (environmental burden) indicators. We measured a total of 21 impact categories in this report, including eight environmental indicators and 13 toxicity indicators. For brevity, here we present only a summary; for the full results, please consult the main report. In the baseline scenario:

- The use of 1 kg of polyethylene terephthalate (PET) (with 2.4 percent recycled content) provides for the delivery of 27.9 L of California-average beverage.
- The product system generates 119.6 MJ (net) of primary energy demand, 20,500 kg·km of demand for freight services, produces 0.56 kg of secondary PET and 0.729 kg of solid waste.
- Delivery of the product system results in 5.79 kg CO_2-eq of global warming potential, 58 g SO^2-eq acidification potential, and 8.9 g N-eq of eutrophication potential.

Figure S-2 shows the breakdown of energy demand by life cycle stage for the baseline scenario.

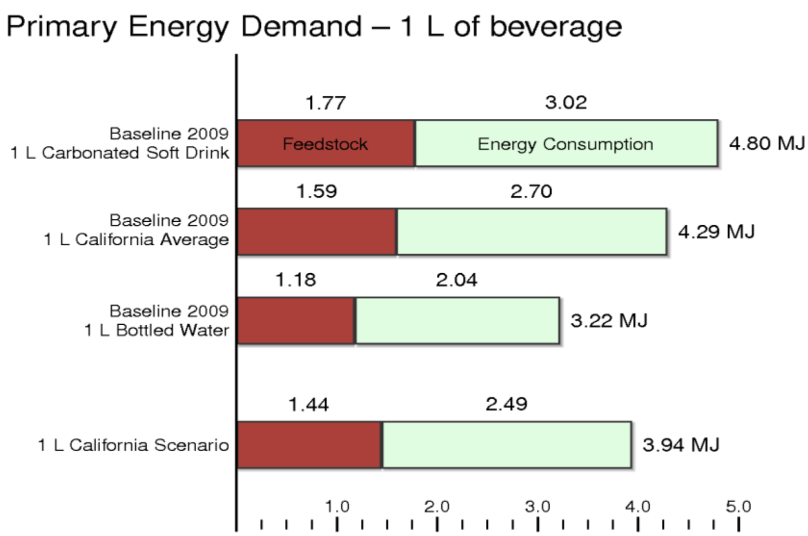


Figure S-3 Energy requirements per liter for different product types.

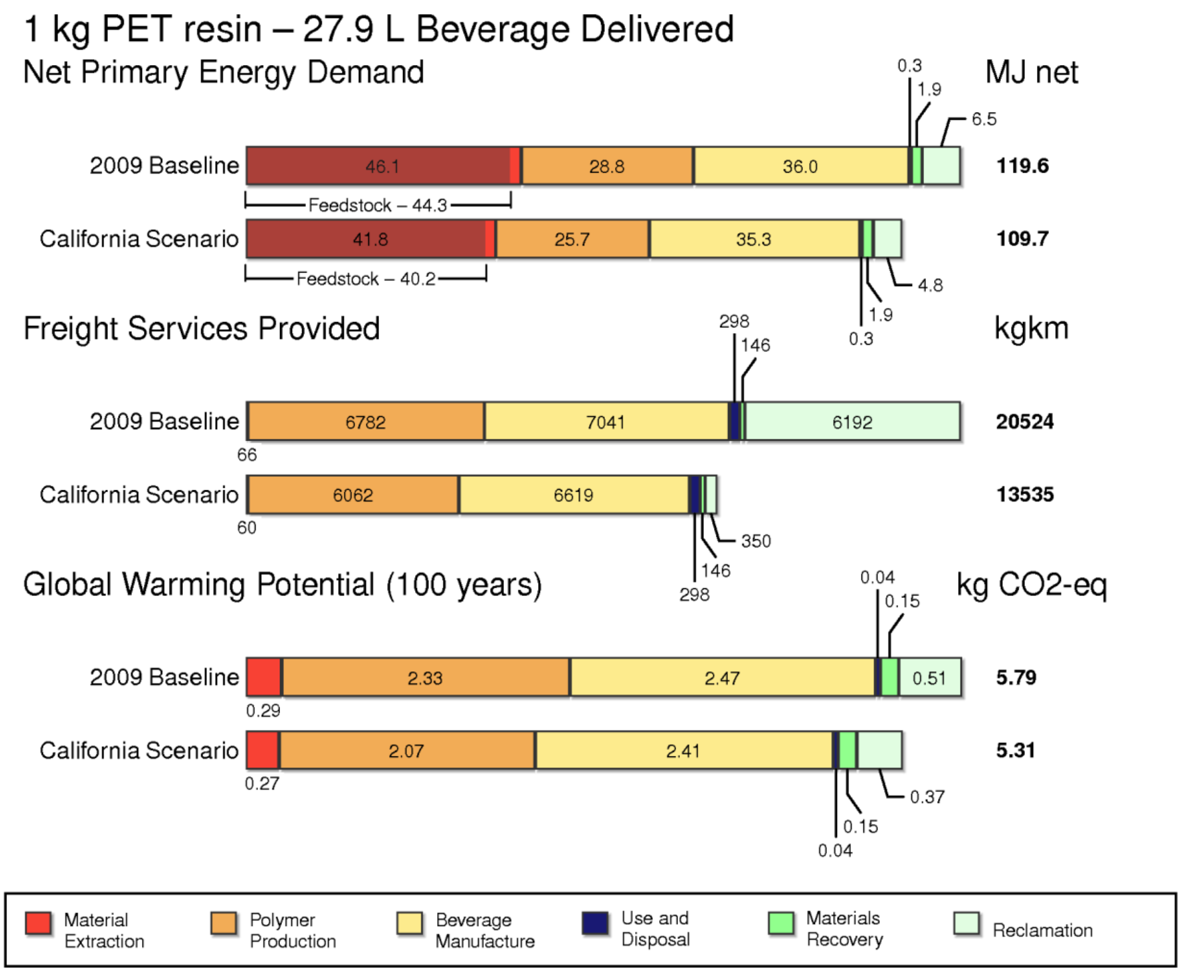


Figure S-4 Comparison of the Baseline and California alternative scenarios under three different indicators.

On a volume of beverage basis, delivery of one liter of California-average beverage has a primary energy demand of 4.29 MJ (net), requires 737 kg·km of freight services, and produces 20 g of secondary polyethylene terephthalate (PET) and 26 g of waste. One liter of bottled water has a primary energy demand of 3.22 MJ (net), requires 565 kg·km of freight services, and produces 14 g of secondary PET and 19 g of waste. One liter of carbonated soft drink has a primary energy demand of 4.80 MJ (net), requires 825 kg·km of freight services, and produces 23 g of secondary PET and 29 g of waste. These results are summarized in Figure S-3 and in Table 3.1.

Under the California alternative scenario:

- The use of 1 kg of PET (with 15 percent recycled content) provides equivalent services to the baseline scenario—the delivery of 27.9 L of beverage. However, it requires less primary polymer.
- This system generates 109.7 MJ (net) of primary energy demand, requires 13,500 kg·km of freight services, and generates 0.44 kg of secondary PET and 0.715 kg of solid waste.

- Much of the reduction in energy demand arises from the increased use of recycled material in beverage manufacturing.
- The alternative scenario results in 5.31 kg CO_2-eq of global warming potential, 52 g SO_2-eq of acidification potential, and 8.7 g N-eq of eutrophication potential.

The Baseline and California scenarios are compared in brief in Figure S-4.

Toxicity-related impacts were more difficult to generalize and are discussed below.

2.6 Recycling

Two different types of recycling can be distinguished in this product system. The first, “closed-loop recycling,” also known as “bottle-to-bottle” recycling, indicates the use of secondary material in the beverage bottle product system. This is distinct from “open-loop recycling,” in which secondary polyethylene terephthalate (PET) from bottles is used in a different product system. Because of the stringent technical requirements of injection stretch blow molding, there is limited market demand for bottle-to-bottle recycling, and most secondary PET is open-loop recycled.

Closed-loop recycling carries immediate environmental benefits because the secondary material directly displaces primary material. The benefits of open-loop recycling are more difficult to assess because it is less clear that primary material production is reduced as a consequence. In our study, we report the amount of secondary PET that is open-loop recycled, and we report the environmental burdens associated with producing an equivalent amount of primary PET. In some circumstances it may be appropriate to treat these impacts as an “avoided burden” that does not occur because of recycling. If an avoided burden credit is given to the product system, closed-loop recycling and open-loop recycling are effectively identical.

The baseline scenario results in the production of 0.547 kg of secondary PET that is open-loop recycled. This has the potential to avoid 36.5 MJ of primary energy demand and 1.38 kg CO2-eq of global warming potential through displaced primary production. In the California scenario, 0.436 kg of secondary material is open-loop recycled. This has the potential to avoid 29.1 MJ of primary energy demand and 1.10 kg CO_2-eq of global warming potential.

2.7 Analysis and Interpretation

The results show that the majority of inventory requirements are associated with the pre-consumer life cycle stages (including resource extraction, polymer production, and beverage manufacture and distribution), which together account for 93 percent of primary energy demand and 87 percent of delivered energy. Many environmental impacts, such as global warming potential and acidification potential, largely mirror energy demand, and pre-consumer stages are the dominant sources of impacts in those categories.

Post-consumer activities (disposal, materials recovery, and reclamation) were dominant in eutrophication potential, and in a number of toxicity categories. The material recovery stage, which includes the operation of low-impact recycling centers and collection vehicles, as well as

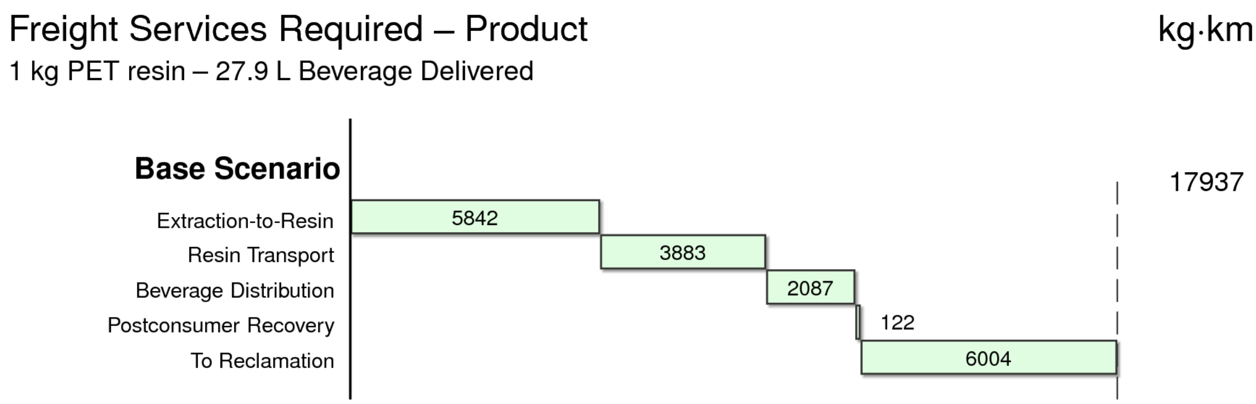


Figure S-5 Freight services used in transporting the product over its life cycle, by transportation step (freight services required upstream in the supply chain and for the fuel production cycle are excluded).

the consumer's transportation to drop-off locations, made a comparatively small contribution to life cycle impacts. Consumer transportation was found to be the most significant contributor to energy-related environmental impacts within the materials recovery life cycle stage because of the low efficiency of private vehicle transportation. However, even with the contributions from consumer transport, the material recovery stage was a small contributor to environmental impacts, making up less than 10 percent of life cycle impacts in almost all categories. The exceptions were in eutrophication potential, which was due to the landfilling of polypropylene caps not recycled, and certain toxicity categories.

Freight services were required in approximately equal proportions by three different life cycle stages: polymer production, beverage manufacture, and reclamation, with other stages requiring relatively small amounts. These stages represent delivery of crude oil and natural gas to polymer facilities, resin transport and filled beverage distribution, and transport of post-consumer polyethylene terephthalate (PET), respectively. Transportation fuel represents approximately 12 percent of primary energy demand and about 30 percent of delivered energy. Freight services required per transportation step are shown in Figure S-5.

We used landfill processes originating from the Ecoinvent database (and representing Swiss conditions) because there is no adequate process inventory for U.S. landfills available to us. Because Swiss waste management practices are significantly different from American practices, particularly regarding their use of incineration to process groundwater remediation sludge, the emissions inventories from these processes are not well-suited to the product system under study. There is a need for a comprehensive study of American landfills to develop accurate process inventory models.

2.8 Toxicity Category Scores are Inconsistent

Toxicity impacts were dominated by heavy metal flows. These are strongly correlated with electricity production and the production of sodium hydroxide, used as a detergent in the reclamation stage. Production of galvanized steel baling wire also manifested significant toxicity impacts due to heavy metals. However, our closer review of toxicity impact indicators casts doubt on their accuracy, and we encourage the reader to interpret the results with caution.

Close inspection of toxicity impact category scores, combined with sensitivity analysis of our inventory data, led us to conclude that toxicity impact scores included in this report are an unreliable basis for comparison of life cycle stages or different scenarios. There are three primary reasons for this conclusion:

1. When applying the same impact assessment methodology to three different polyethylene terephthalate (PET) polymer cradle-to-gate inventory data sets, the results differ over several orders of magnitude. This suggests that inventory data are reported with widely varying completeness criteria. In particular, processes in the Ecoinvent database are likely to have far higher toxicity impact scores than processes from the U.S. LCI database according to the TRACI methodology, and have much lower impact scores according to the CML methodology.

2. Heavy metals vastly dominate organics in all toxicity categories, even though petroleum refining and polymer production involve organic substances known to be toxic. The elementary interpretation of this observation is that organic substances associated with plastic production do not present a toxic threat in comparison to heavy metals. However, the following interpretations are also possible:

    - that organic substances are poorly represented in process inventories;
    - that data gaps exist which conceal the impacts of organics; or
    - that methodological decisions in impact characterization cause results to amplify the impacts of heavy metals relative to organics.

    It is beyond the scope of this report to evaluate these possibilities in detail.

3. Many indicator scores are dominated by one or a few flows. This suggests that the omission or erroneous reporting of one or a few significant flows could dramatically alter the results, adding to concerns about the thoroughness of inventory data.

As a consequence of these observations, we urge caution in interpreting the toxicity indicator results presented in this report. Inconsistencies in system boundary definitions or modeling methodology between the U.S. LCI and Ecoinvent process inventory data sets probably led to inaccuracies in these indicators. In particular, both sodium hydroxide production and baling wire production were drivers of toxicity scores, but they were drawn from Ecoinvent processes, suggesting that their significance in the results may be spurious. Another example is found in the flow of barium to fresh water in U.S. LCI extraction processes, which is the most significant contributor to several CML impact scores, but is not corroborated by the TRACI database and is not represented in Ecoinvent. Without further research to accurately characterize the toxic impacts of the PET bottle system, it is not possible to say whether the results accurately reflect the product system’s impacts or whether they are artifacts of database errors.

Life Cycle Model (GaBi)

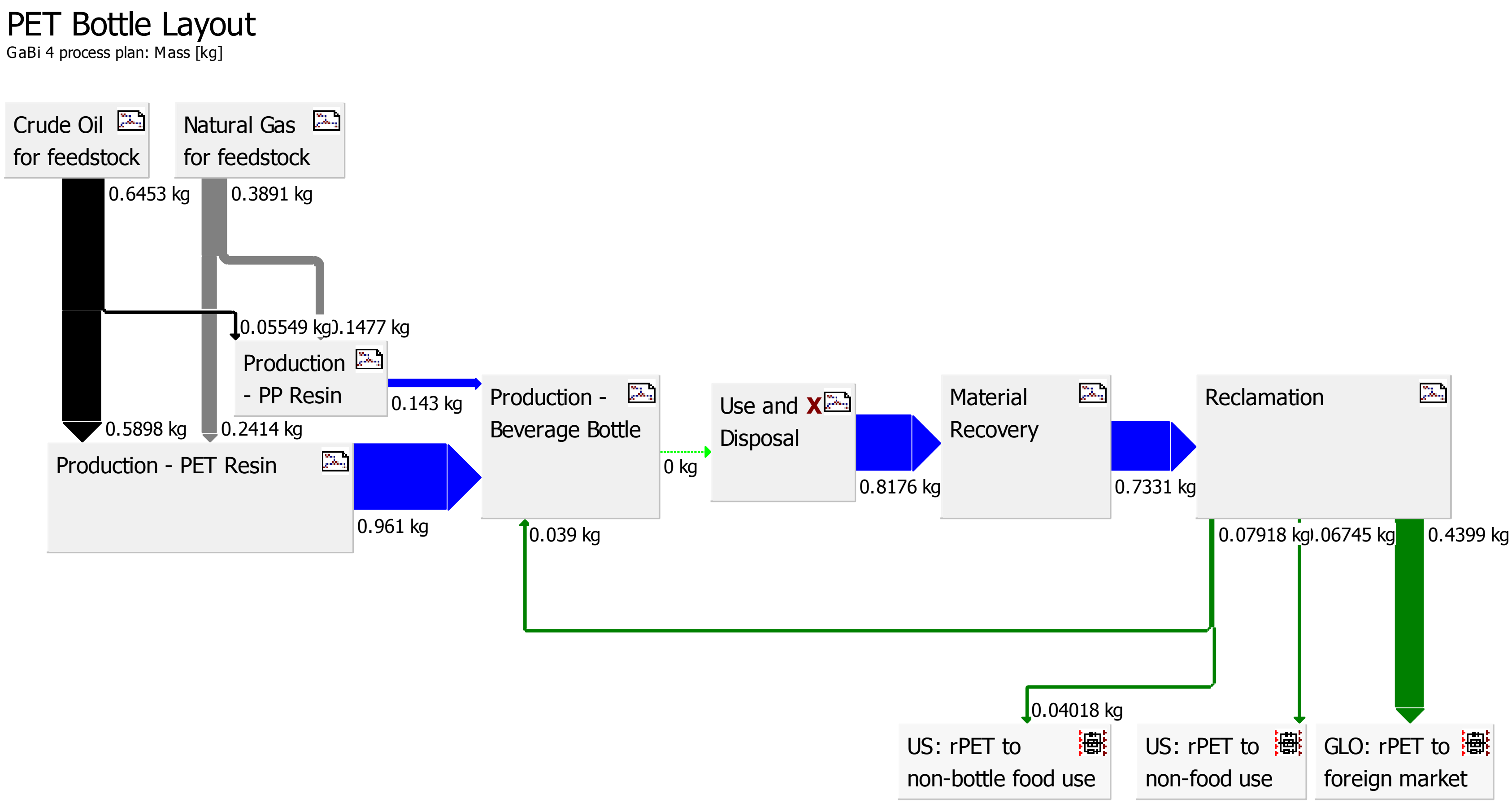


Figure 1.1 GaBi Life cycle model showing mass flows under the 2009 baseline scenario, for bottles made from 1 kg of PET resin.

3 Scope and Methodology

3.1 Process LCA According to the International Standard

The goal of this study was to characterize the resource requirements and environmental impacts associated with the use of the thermoplastic polymer polyethylene terephthalate (PET) to manufacture disposable beverage bottles delivered to the California market. The report has been prepared in accordance with the international standard for life cycle assessment (International Organization for Standardization, 2006). The intended audience for the report is the personnel of the California Environmental Protection Agency, Department of Toxic Substances Control (DTSC).

Much ongoing work in life cycle assessment (LCA) is guided by ISO 14044 and related documents, international standards published by the International Organization for Standardization (ISO). The standards describe a methodology for LCA that is oriented around a series of *unit processes* which take in resource and energy inputs and transform them into a “unit” of output(s) while producing wastes and emissions. Unit processes are generally considered to be linear, meaning that the inputs and outputs can be scaled up together. In other words, producing twice as much output requires precisely twice as much input and produces precisely twice as much waste and emissions.

Completion of an LCA includes four phases:

- **Goal and scope definition**, including a statement of the system boundary, functional unit, and aspects of the inventory and life cycle environmental impacts to be considered;
- **Inventory analysis**, which includes identification and description of the network of *unit processes* and *flows* which make up the product’s life cycle;
- **Impact assessment**, in which the environmental significance of inventory flows is estimated; and
- **Interpretation** of the results.

3.2 Overview: The life cycle of a PET bottle

Polyethylene terephthalate (PET) is made from crude oil and natural gas, in the form of the commodity chemicals xylene and ethylene. The polymer is made through the polycondensation of terephthalic acid (made from xylene) with ethylene glycol (made from ethylene). In the U.S., PET manufacturers are centered in the southeast, with more than 80 percent of capacity located in North and South Carolina as of 2007 (SRI Consulting, 2007).

PET resins are distinguished on the basis of their intrinsic viscosity (IV), an engineering measurement of the mean polymer chain length (Kuczenski and Geyer, 2010). The IV of PET can be increased through a process called solid-state polymerization, in which flakes of PET are held near their melting point for an extended period of time. “Bottle-grade” (high-IV) PET suitable for manufacture of plastic bottles is distinguished from amorphous or fiber-grade (low-IV) PET in international trade and customs on the basis of IV (US International Trade Commission, 2009).

In contrast to polyethylene terephthalate (PET) polymer manufacture, beverage bottling is a much more geographically distributed industry with operations in every state (U.S. Census Bureau, 2010). Beverage bottles are made by the process of injection stretch blow molding (ISBM). ISBM is a two step process: first a hollow “preform” is made by injection molding of PET solid state resin. The preform is heated to near its melting point and then simultaneously inflated with compressed air and stretched inside a chamber. Upon contact with the walls the resin cools, taking the shape of the chamber.

Because empty bottles are bulky and inefficient to transport, it is assumed that bottles are manufactured and filled at the same facility. Bottles are joined to caps (often made of polypropylene or high-density polyethylene) and labels (made of low-density polyethylene film, other plastics, or paper, and attached to the bottles with adhesives). Bottles are then filled and distributed by truck. Our model excludes the retail and use stages of beverage bottles. Although all bottles are assumed to be chilled once prior to consumption, energy use and impacts due to the refrigeration and display of chilled bottles is not estimated.

Most PET bottles sold in California are included in the state’s beverage container recycling program. Consumers pay a deposit on each bottle included in the program (currently 5 cents for bottles below 24 oz and 10 cents for bottles 24 oz or larger) which they can redeem by returning the bottle to a collection facility for recycling. Around 75 percent of recycled bottles are collected in this way. Many California residents also have access to curbside recycling programs. In these programs, bottles, along with other recyclable materials, are collected in a single stream by trucks and delivered to materials recovery facilities, where they are sorted from other materials. After recycling, bottles are compacted into bales and sold to reclaimers. About 70 percent of CRV bottles made of PET are presently recycled in California, dramatically higher than the national average collection rate of about 28 percent (Luther, 2009; NAPCOR, 2010).

Minimizing contamination is of utmost importance in PET recycling because the presence of certain contaminant materials can cause defects or otherwise degrade the reclaimed material even if present in very small concentrations (Awaja and Pavel, 2005). Polyvinyl chloride (PVC) and polylactic acid (PLA) are particularly problematic contaminants because they are difficult to distinguish from PET during sorting. PVC contamination leads to the production of hydrochloric acid, which degrades PET recyclate. PLA has a much lower melting point than PET and can foul PET during high-temperature drying.

The U.S. exports about half the postconsumer PET bottles collected. However, the percentage of bottles exported from within California is probably higher (NewPoint Group, 2007). This is in part because of the easy access to Asia-bound oceangoing freight, which is economical with respect to overland shipping to the southeast U.S.

PET reclamation consists of sorting, grinding, washing, density separation, drying, a final sort, and reconstituting the reclaimed material. Sorted bottles with contaminants removed are ground up into “dirty flake,” which often includes other plastics from caps and labels. Polypropylene and polyethylene are termed “polyolefins” or simply “olefins” and can be easily separated from PET because of their low density (polyolefins float; PET sinks). The dirty flake is washed in a caustic bath, usually with sodium hydroxide as a caustic agent, and then polyolefins are sorted using float separation. The olefin fraction can be recovered and recycled. The sorted PET flakes are dried in an oven. The dry flakes can then be put through an additional sorting stage. The output of this process is called “clean flake.” Clean flake can be re-crystallized or re-granulated, it can undergo solid-state polymerization to increase the intrinsic viscosity (IV), or it can be used as-is in some applications. The yield for the reclamation process is about 80 percent.

3.3 Life Cycle Modeling

The life cycle is modeled as a sequence of basic processes, each of which may require the extraction of materials or the delivery of support services. Sequential, related basic processes are grouped together to represent a life cycle “stage.” Life cycle stages are described in terms of the resources and energy they require and the environmental impacts that have been allocated to them.

The life cycle stages included in our model are:

- Extraction of fossil feedstocks
- Production of polymer resins
- Beverage bottle manufacture and beverage distribution
- Use and disposal
- Material recovery
- Reclamation of secondary material.

We describe each stage in terms of its material requirements and environmental impacts.

3.4 Definition of Key Terms

3.4.1 Inputs and outputs

Terms defined: Elementary flow
Intermediate flow
Product flow
Supply chain flow

Accepted life cycle assessment (LCA) practice recognizes two main types of flows: **elementary flows** (sometimes called primary flows) are flows between the natural environment and the human techno-economic system. These flows include extracted natural resources, energy from natural sources, and emissions into the natural environment. Elementary inputs are drawn from the environment “without previous human transformation,” while elementary outputs return to the environment “without subsequent human transformation.” (ISO 2006). In contrast, **intermediate flows** represent flows between processes. Intermediate flows are all outputs of some industrial process and are all inputs to some other process.

Intermediate flows can further be divided into **product flows** and **supply chain flows**. Product flows represent material flows that at some point in the process chain are part of the product being modeled. Supply chain flows are used in processes but do not become (or never were) part of the product. As an example, consider a plastic molding process. The raw plastic, as well as any additives or dyes, are product flows, whereas the electric energy, molding machinery, cooling water and other similar flows are supply chain flows. In this paper we refer to some supply chain flows as "services." For instance, we speak of "transportation services," "energy provisioning services," and "waste disposal services." All of these services represent intermediate flows that do not become part of the product but are still necessary for its manufacture. The scope of the study is strongly determined by the selection of supply chain flows to include or omit.

3.4.2 Processes

Terms defined: Extraction process
Basic process
Support process

The processes in our model can be grouped into three categories: extraction processes, transformation processes, and support processes. They are distinguished by the types of flows they require and produce.

Extraction processes convert resources into useful forms. In other words, they have no product inputs, only supply chain or "service" inputs. The material output of an extraction process originated in an elementary input. Extraction processes are made explicit only for product flows (i.e. extraction of materials that become part of the reference flow).

Basic processes (or gate-to-gate processes) transform a product input flow into a product output flow, making use of supply chain inputs provided by support processes. The flow inventories for basic processes include only emissions which occur directly from the facilities where the processes take place—emissions for upstream processes and supporting processes are included elsewhere. We model basic processes as "black boxes" in this report.

Support processes provide necessary services to perform basic processes. Support processes are modeled as cradle-to-service, so all upstream processes required to provide the service are "rolled up" into the process. Each support process thus includes no intermediate inputs and exactly one intermediate output.

3.5 Scope and System Boundary

Figure 1.2 shows our model of the PET bottle system. Our study's scope includes the extraction of fossil fuels for plastic resin feedstock, production of virgin resins, manufacture of bottles and beverages, distribution of beverages to retail, disposal by the consumer into either municipal waste or recycling, material recovery of recycled bottles, and reclamation of recycled polyethylene terephthalate (PET) to form secondary resins. The life cycle assessment (LCA) includes the impacts generated by these processes directly, as well as the impacts due to support and infrastructure processes required to perform the transformations. A core model is used by all life cycle stages to provide resource and emissions data for fuel production, electricity, combustion, and transport.

We present an *attributional* LCA, meaning that our results are meant to indicate the actual environmental impacts that are likely to be caused by the product system as it exists. Avoided production of primary material due to the reclamation of secondary material is *not* included—no processes in our model have negative impacts. Instead, any secondary material produced is a *co-product* of the product system. The benefits of recycling can be computed in subsequent studies through allocation of impacts between the plastic bottle system and the product system that uses the secondary PET produced (see section 1.5.2 below).

The process inventory data in our model come from outside sources, and so our results reflect methodological decisions made by the authors of those sources. Our system boundary is largely defined by these data sources. In particular, the methodology of Franklin Associates (abbreviated FAL after their Web address, http://www.fal.com) figures prominently in the U.S. LCI database used as the core of our study.

The following aspects of the product system were systematically excluded from the model:

- Construction of capital equipment used in extraction, refining, manufacture, distribution, materials recovery, reclamation, and supporting processes;
- Land use associated with resource extraction;
- Public infrastructure including roads, waterways, water distribution;
- Private infrastructure including fuel and petrochemical distribution, electric power distribution, telecommunications;
- Facility overhead such as lighting, heating, and maintenance;
- Administrative overhead such as office support, human resources, and finance;
- The products of direct human activity.

In addition, certain aspects of the product system are omitted from consideration because data are not available or because they lack relevance to the study's scope:

- Manufacture of the liquid beverage;
- Impacts associated with retailing and marketing the beverage;
- Secondary and tertiary packaging;

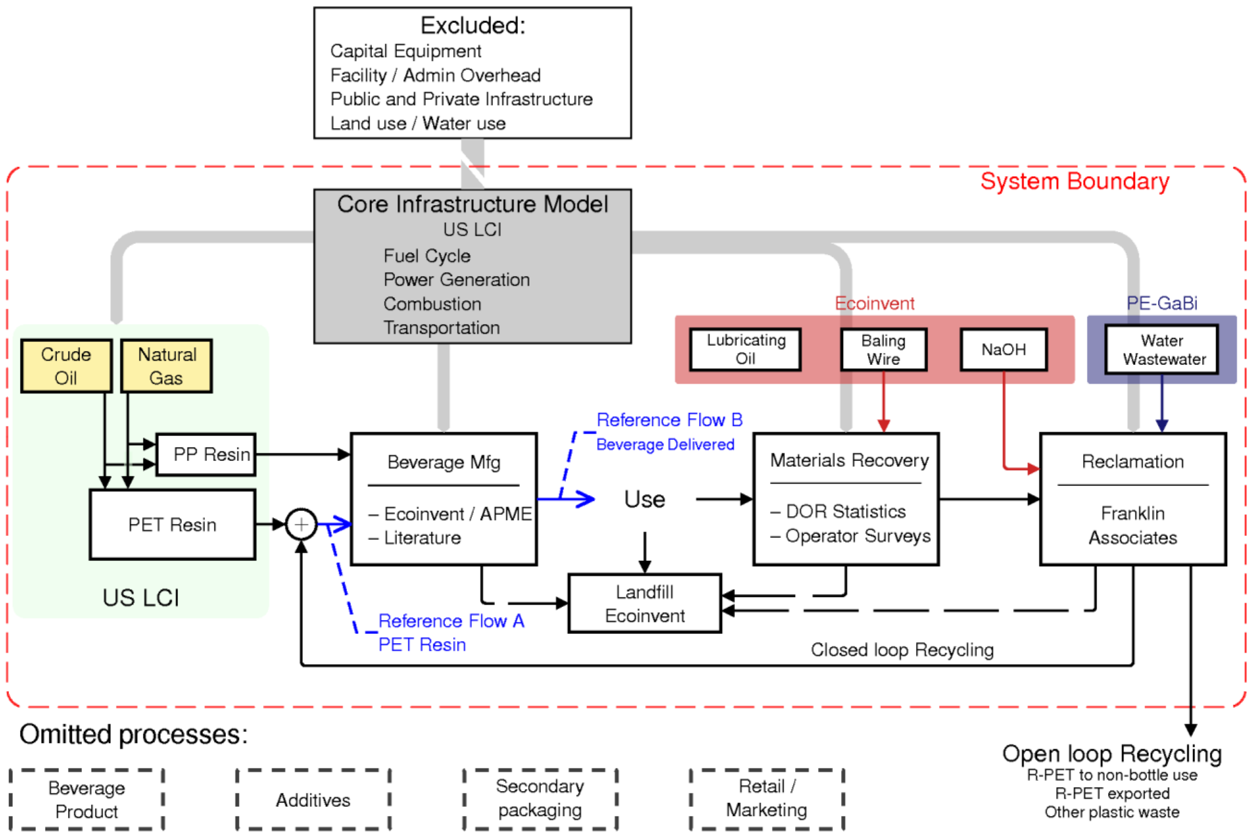


Figure 1.2 Detailed system diagram showing data sources and model boundaries.

- Transportation of manufacturing waste to landfill (transport of post-consumer waste is included);
- Certain chemicals, additives and miscellaneous supplies.

Secondary packaging, such as cardboard and plastic film used to package pallets of beverage bottles, is not included in our model and may have significant impacts. A recent study of bottled water indicated that secondary packaging contributed approximately 13 percent of the energy requirements and 18 percent of solid waste generation associated with the product system (Oregon DEQ, 2009).

3.5.1 Water Use

Although inclusion of water use in the life cycle model is desirable, it is not included in many significant data sets, including the U.S. LCI database. In addition, of the process inventories which do include water use data, none or very few appear to be representative of California conditions. Consequently, we have omitted water use from our impact assessment and only report it in cases where the data are applicable to the current study. No inferences should be made from this report regarding water use associated with the delivery of the product being modeled.

3.5.2 Allocation of Recycling Benefits

Life cycle analysts commonly recognize two forms of recycling. “Closed-loop” recycling denotes a product system in which the post-consumer waste is recycled within the same system. In the present model, that would mean “bottle-to-bottle” recycling of polyethylene terephthalate (PET). “Open-loop” recycling indicates the use of recycled material in another product system, such as “bottle-to-fiber” recycling. In closed-loop recycling it is possible to see an actual “loop” of material flows from a post-consumer stage to a pre-consumer stage in a system diagram, as is evident in Figures 1.1 and 1.2. The benefits of closed-loop recycling manifest directly in the model as a reduction in the primary material required to deliver a fixed service.

Open-loop recycling is more problematic to model in a life cycle assessment (LCA). A product system which produces recycled material essentially has two products: the primary product, which delivers the functional unit of the system, and the recycled material (called ‘secondary‘ material) that becomes available to another product system at the product’s end of life. The environmental impacts which occurred during the product’s life cycle may be apportioned between these two products. This is referred to as “co-product allocation” in the ISO standard.

There is no single agreed-upon methodology for allocating impacts to recycled material, though there are several common approaches (Shen et al, 2010). The first, often called the “cut-off” method, simply draws a line at one point in the product life cycle. Everything before the line is assigned to the primary product system; everything after the line is assigned to the secondary product system. In this case, *all* the impacts of primary material production are assigned to the primary product system, with the full benefits of using recycled material falling to the secondary product system. In this case, product systems which are recyclable do not register any environmental benefits arising from recycling.

An alternate approach, known as the “avoided burden” method, awards a credit to the primary product system equal to the amount of primary material that *could be replaced* by the use of the recycled material. This creates an accounting problem. Because no emissions were actually withdrawn from the environment, the credit awarded to the primary product system must be compensated by an “added burden” charge to the secondary product system. In other words, the effect is the opposite of the cut-off method in that the *primary* product system is awarded the full benefits of recycling. The secondary product system (which uses the recycled material) would have to account for it *as if it were primary material*, because the credit for recycling had already been awarded to the primary system. Both of these approaches are in dispute. Compromise approaches to “split the difference” between the two product systems have also been developed. An illustrative example can be found in Shen et al (2010), which considers open-loop recycling of PET bottles in depth.

Because the current study is intended to be attributional, i.e. to document environmental emissions that actually occur, we used the “cut-off” method in which the full impacts of material production, manufacturing, use, recycling and reclamation are all awarded to the primary system. We did not include any avoided burden credits for recycled material, and instead modeled beverage consumption as a multi-output system which produces two co-products: delivery of beverages and production of secondary PET.

In order to facilitate co-product allocation in subsequent studies, we also computed the impacts of primary polyethylene terephthalate (PET) production which could be avoided through use of the secondary material. We report these values in Table C.8, in Appendix C. Subsequent studies should use the figures in this table to compute the environmental impacts that can be attributed to producing primary PET within our model. In the case where the secondary PET produced is assumed to displace primary PET in another product system, these impacts may be subtracted as an avoided burden if appropriate.

3.6 Reference Flows and the Functional Unit

Our study evaluates the impact of beverages packaged in PET bottles with polypropylene (PP) caps and oriented polypropylene (OPP) labels; retailed, consumed, and disposed in California; and subject to California's CRV container deposit program. The weights of bottle components (bottle, cap, and label) were determined for three different product categories by direct measurement.

We adopted a simplified model of the California beverage market to develop our scenarios. The scenarios themselves are described in Section 1.7. We estimate the market share of three different types of beverage based on regional beverage market statistics published in Beverage World Magazine (Anonymous, 2006) and trade publications (Beverage Digest, 2008). It assigns 60 percent of the California liquid refreshment beverage market to bottled water, 16 percent to carbonated soft drinks, and 24 percent to juices, teas, sports drinks, and other PET-packaged beverages. We assume *typical*, not *average*, container sizes because of a lack of sales and marketing data. Table 1.1 describes the key parameters which determine the weight of polymer required in each product category.

Table 1.1 Bottle component weights by product category, and beverage market assumptions.

	Bottled Water	Carbonated Soda	Juice / Sports	Average
Container size (L)	0.500	0.591	0.591	0.530
PET (g)	12.8	23.9	29.5	18.6
PP cap (g)	1.5	2.4	3.8	2.2
OPP label (g)	0.5	0.5	0.5	0.5
Market Share[a]	60%	16%	24%	-
Volume per kg of PET (L)[b]	38.2	24.2	19.6	27.9

a - Beverage World Magazine (Anonymous, 2006) and Beverage Digest (2008).
b - These figures represent the volume of containers that can be produced with 1 kg of resin.

The average recycled content of PET bottles is assumed to be 3.9 percent, based on the amount of secondary material used in bottles in comparison to total bottle sales (National Association for PET Container Resources, 2010). This value reflects an estimate of the degree of investment in recycled-content bottles by beverage manufacturers. The California recycling collection rate, in contrast, describes the recovery of post-consumer bottles. While California's collection rate has increased significantly over the past decade, the use of secondary material in bottles has increased only gradually (Kuczenski and Geyer, 2010).

Figure 1.2 highlights two reference flows. Reference flow A represents primary and secondary polyethylene terephthalate (PET) at the input to the beverage manufacture process, and Reference flow B represents packaged beverages at use. We can define the functional unit based on either of these flows. In the base case of our model, 0.961 kg of virgin PET is combined with 0.039 kg recycled PET during beverage manufacture. Roughly 22 g of PET is lost because of manufacturing yield losses. The remaining 0.978 kg of PET bottles contains 27.9 L of beverage under our average consumption model.

Using the ad hoc assumption that a typical beverage is transported an average of 10 km between purchase and consumption, and using the above assumptions about the market share of different product categories, 1 kg of PET polymer provides 0.279 metric ton-kilometers (t·km)[1] of freight service to the purchaser in the form of transporting beverages.

Table 1.2 Description of the scenarios modeled in the study. The 2009 Baseline reference flows of 1kg PET resin and 27.9 L of beverage delivered are highlighted.

	2009 Baseline	**California Scenario**	**2009 - BW Variant**	**2009 - CSD Variant**
Scenario Description:	2009 Collection statistics	15% Recycled Content / CA End-of-Life	Bottled Water	Carbonated Soft Drinks
Inputs:				
Total weight of PET Resin [kg]: **Reference flow A**	**1.00**	1.00	26.18	41.35
Weight of secondary PET [kg]: (closed-loop recycling)	0.039	0.150	1.02	1.61
PET Recycled Content:	3.9%	15%	3.9%	3.9%
Weight of PP [kg]:	0.143	0.143	4.03	4.94
Outputs:				
Contained Volume [L]: **Reference flow B**	**27.9**	27.9	1,000	1,000
Number of Containers:	52.6	52.6	2,000 (0.5 L)	1,692 (20 oz / 591 mL)
R-PET co-product [kg]: (open-loop recycling)	0.55	0.44	14.5	22.5

3.7 Scenario Modeling

We present one baseline scenario representing California-average conditions for the year 2009,

[1] All references to tons or tonnes in this report refer to metric tons, or 1,000 kg, unless they are specified as "short tons."

and one alternative scenario (summarized in Table 1.2). The baseline scenario describes the use of 1 kg of polyethylene terephthalate (PET) resin (comprising 0.961 kg primary resin and 0.039 kg secondary resin) and 0.143 kg of polypropylene (PP) to package 27.9 L of California-average beverage. We also report two variants to the baseline scenario. In the bottled water (BW) variant, 26.2 kg of PET and 4.03 kg of PP are used to contain 1,000 L of bottled water. In the carbonated soft drink (CSD) variant, 41.4 kg of PET and 4.94 kg of PP are used to contain 1,000 L of carbonated soft drinks. Post-consumer recovery and reclamation are modeled to approximate real-world conditions in 2009, in which the bulk of post-consumer bottles are exported to Asia via ocean freight.

The alternate scenario, labeled CA, is intended to describe the potential reduction in environmental impacts that could occur if reclamation and utilization of secondary material were improved in California. In this scenario, we model a hypothetical bottle produced in a California facility with 15 percent recycled content. All post-consumer recovery and reclamation occurs within California, and no postconsumer bottles are assumed exported to Asia or shipped by freight to reclaimers on the East Coast. The portion of secondary PET not used in bottles is assumed to find beneficial use in non-bottle food packaging within California.

The parameters used for modeling all scenarios are summarized in Section 2.4.

3.8 Process Inventory Data Sources

Our life cycle model is made predominantly from existing process inventory data. The data sources we used are described here. Inventories for processes specific to the PET bottle product system in California were generated separately and are described in Section 2.3.

US LCI Database. Our report uses the U.S. Life Cycle Inventory (U.S. LCI) database maintained by the National Renewable Energy Laboratory as its main source for process inventory information (Anonymous, 2008). The U.S. LCI database contains a nearly complete set of coordinated process inventories which are designed with a common set of assumptions and boundary conditions. This enables them to be used together to form a self-consistent model.

Most of the data in the U.S. LCI database, including core infrastructure processes, was collected and contributed by Franklin Associates (FAL), a division of Eastern Research Group (ERG) and a prominent U.S. environmental consulting firm. The American Chemistry Council commissioned FAL to perform a life cycle inventory study for several different polymers produced in the United States. The results of that study were contributed to the U.S. LCI database and form the core of our analysis (Franklin Associates, 2007).

The U.S. LCI database has not undergone comprehensive peer review. However, the core model was included in a study of drinking water for the Department of Environmental Quality for the state of Oregon which was peer-reviewed (Franklin Associates, 2009). The reviewers' comments were included in the body of that report. The components of the study which share content with the U.S. LCI database were not discussed by the reviewers. Most of the data for the polymer production dataset dates from the late 1990s and early 2000s.

Ecoinvent. The Ecoinvent database is maintained by the Swiss Centre for Life Cycle Inventories and is available for use with a licensing fee (Frischknecht et al., 2007). The Ecoinvent database is primarily Europe-focused. It includes a much broader scope of processes, including infrastructure processes such as capital equipment production.

We used Ecoinvent data in cases where there were significant data gaps in the U.S. LCI model, particularly for the disposal of plastic waste in landfill or incineration. Ecoinvent processes were also used for the production of certain supplies, including lubricating oils, sodium hydroxide, and galvanized steel baling wire.

PlasticsEurope. Formally the Association of Plastics Manufacturers in Europe (APME), PlasticsEurope maintains a life cycle inventory database for plastics manufacture, overseen by Ian Boustead. The full PlasticsEurope data set is incorporated into the Ecoinvent database (Hischier, 2007). We used cradle-to-gate datasets from PlasticsEurope for comparison to evaluate our own results.

PE International. The makers of the GaBi 4 software also maintain a process inventory database. We used PE International data for water supply and wastewater treatment in the PET Reclamation life cycle phase because Ecoinvent appeared to lack a suitable process. (PE International, 2006).

3.9 Data Quality Assessment

Our model includes many parameters which represent variable aspects of the product system, including process characteristics, transportation distances, end of life treatment scenarios, and other aspects. Each parameter was selected based on data from a published source or expert judgments. We evaluated the quality of each parameter and gave it a letter score, ranging from A-E, which reflected the precision of the estimate. The scores are listed alongside each parameter value in Section 2.3. Our scoring system is based on the data quality evaluation performed by Franklin Associates (Franklin Associates, 2007). The scores are described briefly here:

A - Highest Quality (+/- 5 percent). These figures are directly-collected statistically reliable data by a broadly representative trade group or government agency.

B - High Quality (+/- 15 percent). Data collected from a representative sample base and reviewed for accuracy by experts.

C - Good Quality (+/- 30 percent). A combination of empirical data and technical estimates, judged to have a high level of reliability.

D - Mature Estimate (+/- 50 percent). Data are primarily estimated based on technical expertise and may include some supplemental empirical evaluation.

E - Preliminary Estimate (+/- 100 percent). Data are preliminary only and include minimal or no empirical assessment.

It was beyond the scope of this project to perform an in-depth investigation of the quality of process inventory data contained in the above databases. We tried to select the most representative processes in each case throughout the model construction. However, each process contains dozens to hundreds of elementary flows representing emissions into the environment. These flows were not audited.

3.10 Inventory Indicators

We report the following inventory indicators:

Primary Energy Demand (gross/net) (PE)

The gross or net calorific value of energy resources extracted from the biosphere. For processes which extract renewable energy directly from the environment (i.e. wind, solar, geothermal, hydro), gross and net energy are both taken to be equal to the amount of energy delivered by the process.

Feedstock Energy (gross/net) (FE)

When an energy resource is appropriated for a non-energy use, its energy becomes feedstock energy.

Net Delivered Energy (DE)

When a support process makes available an amount of energy to a basic process, that energy has been "delivered" to the process. The DE reports the amount of process energy required by the process, and the ratio DE/PE represents one measure of the efficiency of the energy delivery infrastructure. This figure reports the energy content of the fuel delivered to its final useful process.

Freight Services Provided (FS)

Freight is modeled as an amount of mass transported a given distance. Freight services are measured in kg·km or t·km. One kg·km represents the service of transporting 1 kg of freight a distance of 1 km. TS measures the amount of freight services that were required in the performance of a given task.

Net Transport Energy (TE)

When an energy resource is used as fuel for a process which produces transportation services (FS), that energy is counted as transport energy and included in this metric.

Secondary Material Produced (SM)

When materials are recycled into secondary resources which may replace primary resources somewhere in another product system (open-loop recycling) they are counted as secondary materials.

Waste Disposal Provided (WD)

Waste from industrial processes does not generally return to the natural environment. Instead it is either landfilled or incinerated. Waste disposal is modeled as a service provided by a support process. This indicator reports the total amount of waste disposal that was accounted for in the model.

GaBi - Net Primary Energy from Renewable Materials

This measurement is built into GaBi and reports the software's best estimate of the amount of renewable energy sources used in producing the product. It is included for comparison with our estimate of primary energy demand. Note: this indicator is reported along with impact results.

GaBi - Gross / Net Primary Energy from Resources

These measurements are built into GaBi and report the software's best estimate of the amount of non-renewable energy sources used in producing the product. They are included because support processes which do not use our core infrastructure model. These figures are consistently 5-8 percent higher than our estimates of primary energy demand because they include the energetic content of mine tailings and waste from coal and uranium mining, and we omit the energy of those flows. Note: this indicator is reported along with impact results.

3.11 Impact Indicators

The purpose of life cycle impact assessment is to characterize the effects of inventory flows on aspects of the natural environment. Impact assessment is performed by first selecting a set of impact categories of interest and then characterizing the significance of each inventory flow to each impact category. Each flow is assigned a "characterization factor" which reflects the significance of that flow with respect to a reference unit.

Impact categories are usually divided into "midpoint" indicators and "damage" or "endpoint" indicators. Midpoint indicators measure the potential to cause harm that arises from a specific emission. They are usually defined with respect to a recognized mechanism for altering the environment. In contrast, endpoint indicators extrapolate beyond the potential effects of emissions to measure the likely damage that may ultimately be caused by a specific emission. Because endpoint indicators depend on models of environmental changes in addition to models of chemical fate and effects, they tend to have greater uncertainty than midpoint indicators.

For example, greenhouse gases are recognized to trap heat in the atmosphere (the "greenhouse effect"), which has the potential to cause global warming. Global warming potential (GWP) is a midpoint measurement of contribution to the greenhouse effect. The global warming potential of a substance is determined by how readily the substance contributes to the greenhouse effect, in combination with how long the substance persists in the atmosphere. Desertification and species extinction are some potential consequences of global warming. An estimate of the loss of ecosystem services due to desertification, species extinction, or other ecological changes caused by global warming would constitute an endpoint measurement of global warming impacts.

Independent research agencies maintain sets of characterization factors for various impact assessment categories. For our study, we used two sets of impact assessment metrics: the CML indicators, produced by the Institute for Environmental Sciences (CML) at Leiden University, the Netherlands (CML-2001); and the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI), developed by the U.S. EPA. Our life cycle assessment (LCA) software uses the November 2009 revision of the CML characterization factors. The TRACI characterization factors were last updated in 2002.

Characterization of toxicity is challenging in life cycle assessment (LCA) because although many substances are known to be toxic, the exact nature of toxicity as well as the quantitative effect of various substances is not well understood. On an individual chemical basis, toxicity is typically approached from a risk assessment framework, i.e. by estimating the risk of adverse effects brought on by a given level of exposure. However, a life cycle accounting of aggregate toxicity impacts requires that the effects of many substances from throughout the life cycle are combined together, a process that is subject to significant uncertainty and modeling challenges. In addition, there must be correspondence between the flows listed in the inventory and the substances characterized in the impact model in order for impact scores to be even minimally accurate. We have included two complete sets of impact category indicators in an effort to detect gaps in inventory or impact assessment data sets.

Our analysis reports only midpoint indicators. We report indicators for the following impact categories:

CML 2001, November 2009 Update
For more information on CML impact categories, please see (2002).

GWP - Global Warming Potential (kg CO_2-Equivalent) [2]

Global warming potential measures the contribution of the product to the release of greenhouse gases such as carbon dioxide and methane. CO_2 is released any time fossil fuels are burned, and energy production is the primary driver of global warming potential.

AP - Acidification Potential (kg SO_2-Equivalent) [3]

Acidification potential measures the release of air pollutants, such as oxides of sulfur and nitrogen, which can become acids in the atmosphere. Release of these substances can lower the pH of rainwater and fog, leading to acid rain.

EP - Eutrophication Potential (kg PO_4-Equivalent)

Eutrophication is the enrichment of nutrients in soil or water. This can lead to an increase in the concentration of bacteria or algae, which depletes water of oxygen and can have deleterious effects on terrestrial plant growth.

ODP - Ozone layer depletion potential (kg R-11-Equivalent);

Certain chemicals that persist for a very long time in the upper atmosphere catalyze the degradation of ozone, which can lead to an increase in solar radiation reaching the Earth's surface. Ozone depleting substances were banned worldwide by the Montreal Protocol, which entered into force in 1989.

POCP - Photo-oxidant creation potential (kg Ethylene-Equivalent);

Photochemical oxidation can occur when sunlight interacts with some volatile organic chemicals

[2] CML and TRACI indicators for global warming potential are equivalent.
[3] CML and TRACI indicators for acidification potential are equivalent up to a scalar multiple. TRACI characterizes AP in terms of moles of H+ equivalent.

in the low atmosphere. This can lead to the creation of noxious air pollutants, including ozone and peroxyacetylnitride, which reduce air quality and can cause smog.

FAETP - Freshwater aquatic ecotoxicity potential (kg Dichlorobenzene (DCB)-Equivalent);

MAETP - Marine aquatic ecotoxicity potential (kg DCB-Equivalent);

TETP - Terrestric ecotoxicity potential (kg DCB-Equivalent);

HTP - Human toxicity potential (kg DCB-Equivalent).

These categories reflect measurements of toxicity through different media. The CML indicator set employs the Uniform Substance Evaluation System (USES) v. 2.0 toxicity model (Huijbregts et al., 2000).

TRACI 2002

The TRACI model is discussed in Bare et al. (2003).

EP-T - Eutrophication air and water, TRACI version (kg N-Equivalent);

This measures a similar phenomenon to the CML EP indicator.

Smog - Smog air (kg NOx-Equivalent);

This is an alternative measurement for photochemical oxidation of volatile chemicals.

HH-Criteria - Human Health / Criteria pollutants / air (kg PM2.5-Eqalent);

This category captures emissions of some of the criteria pollutants used under the U.S. Clean Air Act to compute national ambient air quality. These substances are known to cause chronic and acute respiratory systems, premature mortality and damage to ecosystems. This is the only TRACI category that captures particulate emissions.

HHC-A, HHC-GS, HHC-W - Human Health / Cancer (kg Benzene-Equivalent): releases to air, ground / surface soil, and water.

HHNC-A, HHNC-GS, HHNC-W - Human Health / Non-cancer (kg Toluene-Equivalent): releases to air, ground / surface soil, and water.

ET-A, ET-W - Ecotoxicity (kg 2,4-dichlorophenoxyacetic acid equivalent); releases to air, ground / surface soil, and water.

ET-GS - Ecotoxicity (kg Benzene-Equivalent):

This panel of toxicity impact categories offers an alternative to CML indicators for comparison. TRACI toxicity categories are intended to rank the relative severity of different substances, rather than to identify the likelihood of specific adverse effects.

4 Inventory Modeling

4.1 The core infrastructure model

Many support processes used in our model have a circular dependence on one another. For instance, coal is the source of about half the nation's electricity, but coal mining itself requires electricity. In order to compute the impacts due to energy production and fuel supply, we constructed a core model of the energy production infrastructure which is implicitly required by every other process. Processes within this core model account for a substantial portion of all life cycle emissions in the process model. This model thus carries outsize importance in the context of the full results.

Products of the core infrastructure model include:

- Electricity (U.S. average / WECC production mix / California consumption mix)
- Crude oil extraction
- Natural gas extraction
- Gasoline production
- Diesel fuel production
- Liquefied petroleum gas production
- Residual fuel oil production
- Coal combustion in boiler
- Crude oil combustion in boiler
- Natural gas combustion in boiler
- Residual fuel oil combustion in boiler
- Liquefied petroleum gas combustion in boiler
- Diesel combustion in boiler
- Diesel combustion in equipment
- Gasoline combustion in equipment.

For details about the inventory and impacts of these processes, see Appendix D "Inventory and Impact Indicators for Support Processes" below. The U.S. average electricity grid mix was taken from the U.S. LCI database. The electricity grid mixes for California consumption and Western Electricity Coordinating Council (WECC) were taken from the EPA's eGrid 2007 model (U.S. Environmental Protection Agency, 2009, note 2005 data).

The structure of the core infrastructure model and the process inventories for most of the included processes were taken from the U.S. LCI database and reflect the work of Franklin Associates. As a consequence of the relatively limited scope of the U.S. LCI database, many upstream supply chain processes required for energy production and other industrial activities are not captured in our model. Some gaps in U.S LCI data were filled from other sources, as described here:

- Liquid fuel production is not included in the U.S. LCI database but it is included in published reports from Franklin Associates. We used fuel production data from Franklin Associates (2007), Table A-5, which is similar or identical to the data in the appendix to Franklin Associates (2009), Table A-4.
- Transportation of natural gas and petroleum products by pipeline is not modeled in the U.S. LCI database but energy requirements for these transportation modes are included in published reports from Franklin Associates (2007). We used Table A-6 for the energy requirements of pipeline transportation.
- Waste disposal processes are not included in the U.S. LCI database. We used processes from the Ecoinvent database to model waste disposal both within and outside the core infrastructure model.
- We modeled truck transportation based on data from the EMFAC model produced by the California Air Resources Board. We used our process in place of the U.S. LCI process both within and outside the core infrastructure model (see Appendix B).

Several data gaps remain, including the following:

- Renewable fuel production, with the exception of fuel from biomass combustion, is modeled in the U.S. LCI database as a set of "dummy" processes with no material requirements or environmental impacts.
- Production of uranium fuel for nuclear power is modeled in the U.S. LCI database. However, the U.S. LCI model for electricity production from nuclear power is a "dummy" process like those for renewable energy production.
- The construction of infrastructure for extraction, processing and distribution of fuel is not included.
- Land use and water use are not included.
- Construction, maintenance and disposal of facilities and capital equipment are not included.

4.2 Support Processes

These processes provide services to the basic processes involved in the product life cycle. Many of these processes have to do with energy production or delivery and are contained within the core infrastructure model. Other processes were not present in the U.S. LCI database and were supplemented from other sources. Inventory and impact indicators for support processes can be found in Appendix D.

- Electricity Production (Infrastructure):
    - U.S. Average
    - WECC Production Mix
    - California Consumption Mix.

- Liquid Fuel (Infrastructure):
    - Diesel, at filling station
    - Gasoline, at filling station
    - Residual fuel oil, at refinery.

- Fuel Combustion for Heat Recovery (Infrastructure):
    - Natural gas, combusted in boiler
    - Coal, combusted in boiler
    - Diesel, combusted in boiler
    - LP gas, combusted in boiler
    - Residual fuel oil, combusted in boiler.

- Fuel Combustion for mechanical work (Infrastructure):
    - Gasoline, combusted in equipment

- Transportation:
    - Freight by train (U.S. LCI)
    - Freight by combination truck (see Appendix B)
    - Freight by medium-heavy-duty truck (see Appendix B)
    - Freight by ocean freighter (U.S. LCI)
    - Freight by barge (U.S. LCI)
    - Natural gas by pipeline (FAL)
    - Petroleum products by pipeline (FAL).

- Waste disposal (Ecoinvent):
    - Polyethylene, 0.4 percent water, to municipal incineration
    - Polyethylene, 0.4 percent water, to sanitary landfill
    - Polyethylene terephthalate, 0.2 percent water, to municipal incineration
    - Polyethylene terephthalate, 0.2 percent water, to sanitary landfill
    - Polypropylene, 15.9 percent water, to municipal incineration
    - Polypropylene, 15.9 percent water, to sanitary landfill
    - Plastics, mixture, 15.3 percent water, to sanitary landfill
    - Refinery sludge, 89.5 percent water, to sanitary landfill.

- Water (PE International):
    - Potable water from groundwater
    - Organic wastewater processing.

- Supplies (Ecoinvent):
    - Lubricating oil
    - Baling wire 10AWG (custom)
    - Sodium hydroxide, 50 percent in H_2O, production mix.

4.3 Details about Custom-Modeled Processes

Here we describe the components of the model which were not available in standard databases and were custom-generated for this project. These process models are assumed to be uniform for all scenarios. Each parameter was evaluated for data quality and given a data quality indicator (DQI) from A-E. See section 1.8, “Data Quality Assessment,” for more information.

4.3.1 Beverage Manufacturing

Film extrusion, 1 kg Oriented PP

Data for OPP film extrusion was taken from the Ecoinvent database documentation. Data values themselves originate in a report by The Association for Plastics Manufacturers in Europe (APME).

Film Extrusion Yield:	**0.988**	(Hischier 2007, Table 15.3)	DQI B
Electric power required (MJ/kg):	**4.76**	""	DQI C
Lubricating oil required (kg/kg):	**3.24e-04**	""	DQI D
Natural gas combusted (m3/kg):	**0.0866**	""	DQI C
Residual oil combusted (m3/kg):	**1.72e-05**	""	DQI C

Injection molding, 1 kg PP

Data for PP injection molding was taken from the Ecoinvent database documentation. Data values themselves originate in a report by the Association for Plastics Manufacturers in Europe (APME).

Injection Molding Yield:	**0.994**	(Hischier 2007, Table 15.6)	DQI B
Electric power required (MJ/kg):	**7.55**	""	DQI C
Gasoline combusted (m3/kg):	**2.76e-05**	""	DQI C
Lubricating oil required (kg/kg):	**1.75e-05**	""	DQI D
Natural gas combusted (m3/kg):	**0.357**	""	DQI C
LP gas combusted (m3/kg):	**9.47e-07**	""	DQI C
Residual oil combusted (m3/kg):	**8.61e-06**	""	DQI C

Stretch blow molding, 1 kg PET

Energy requirements for the stretch blow molding process were estimated by comparing the energy requirements reported in three different sources. Boustead (2005) reported that 6.5 MJ/kg were required for stretch blow molding of polyethylene terephthalate (PET). Gleick and Cooley (2009) estimated that 20 MJ/kg of thermal energy were required for the process, amounting to roughly 6.7 MJ/kg of electrical energy delivered. Finally, a survey of product literature and specifications suggested a range of 1.8-6.1 MJ/kg electrical energy were required.

Stretch blow molding yield:	**0.978**	(Hischier 2007, Table 15.6)	DQI B
Lubricating oil required (kg/kg):	**0.00196**	""	DQI D
Electric power required (MJ/kg):	**6.5**		DQI C

Beverage assembly

We did not have access to data on the power requirements of beverage assembly, which includes filling, labeling, capping, and product handling. We elected to model only the chilling of beverages in a refrigerator because this aspect of assembly could be modeled without specific data. Beverages are assumed to be chilled by 20 degrees Celsius exactly once in their life cycle using a refrigerator with a typical coefficient of performance of 3 (one unit of energy as work removes three units of energy as heat). Under these assumptions, 83.6 kJ of thermal energy are removed from each kg of beverage in a process which requires 27.9 kJ of work. Our calculation does *not* include the energy required to maintain refrigeration of bottles for transport, retail, or before consumption.

Electricity for chilling of beverage (MJ/kg):	**0.028**	DQI D
Distance from plastic production to bottler (km):	**3500**	DQI B

Beverage distribution

The distance that filled beverages are transported was estimated from the 2002 Commodity Flow Survey prepared by the U.S. Bureau of Transportation Statistics (Bureau of Transportation Statistics, 2010). Beverages are included in commodity code 078, “nonalcoholic beverages not elsewhere specified and ice.” The value is California-specific.

Beverage distribution from 2002 CFS, 078-- California (km):	**72**	DQI A

4.3.2 Use and Disposal

Use phase

The beverage use phase includes no impacts (‘dummy‘ process). Its only role in the model is to apportion post-consumer bottles between landfill and recycling. The recycling collection rate (the share of bottles that are recycled) is taken from biannual CRV program reports.

Fraction of PET bottles recycled (2009, all scenarios):	**0.73**	DQI A

Municipal waste collection, 1 kg

For fuel consumption associated with municipal solid waste (MSW) collection, see discussion of curbside recycling collection, below. MSW collection was assumed to require 60 percent as much non-transport fuel as curbside recycling collection because MSW has higher density. All post-consumer refuse is assumed to be landfilled in our model, and none is incinerated. Average distance to landfill is estimated based on the formula $\sqrt{\;/\;}$, where A is the state land area and N=258 is the number of active landfills in the state as reported on the CalRecycle Solid Waste Information System (SWIS).

Fuel use, non-transport (liter/kg):	**0.0118**	DQI C
Average distance to landfill (km):	**50**	DQI D

4.3.3 Materials Recovery

PET Recycling

This is a distribution process which apportions recycled polyethylene terephthalate (PET) bottles between the two main recovery routes: curbside collection and redemption at a buyback center. The ratio of curbside recycling to buyback center recycling is taken from volume data provided by CalRecycle.

Fraction of bottles recycled at buyback centers:	**0.76**	DQI A

Curbside collection, 1 kg post-consumer PET

Curbside collection of beverage bottles is accomplished through the operation of fleets of collection trucks which gather commingled recyclables from residential and commercial addresses. Fuel usage by curbside collection fleets was estimated based on a survey of operators in the state of California. Curbside collection was found to require 5.2 U.S. gallons (19.6 liters) of diesel fuel per metric ton of commingled waste collected (volume-weighted average of 7 data points ranging from 1.76-10.3 gal/t). The one-way distance between the point of collection and the next processing stage was estimated based on a geographic analysis of processing facilities in the state (see Appendix B). Fuel use reported here plus fuel use required for transport of the “short haul distance” and “long haul distance” equals total fuel use for curbside recycling.

Fuel use, non-transport (liters/kg):	**0.01981**	DQI B
Short haul distance (all bottles) (km):	**30.4**	DQI B
Long haul fraction:	**0.31**	DQI B
Long haul distance (km):	**348**	DQI B

A N

Materials recovery facility, 1 kg post-consumer polyethylene terephthalate (PET)

Curbside commingled recyclables are taken to a materials recovery facility (MRF) to be sorted. Data for MRF operational energy requirements are scarce. Our data are based on detailed data provided by two California facilities in response to survey requests. Several of these data points are based on single responses, and thus have large uncertainty.

Diesel fuel burned (liter/kg):	**0.000374**	DQI D
Electric power required (MJ/kg):	**0.058**	DQI D
Lubricating oil required (kg/kg):	**1e-06**	DQI E
Natural gas required:	None reported.	
LP Gas required (liter/kg)[4]:	**0.0074**	DQI D
Water required (kg/kg):	**0.0362**	DQI D
Baling service required (kg/kg)[5]:	**1**	

Recycling buyback center, 1 kg post-consumer PET

Most buyback centers are so-called "convenience zone" centers located in the parking lots of supermarkets. These buyback centers are typically minimal, low-impact or no-impact facilities at which consumers can exchange their bottles for receipts, which can be traded for cash in the supermarket. We assume that buyback centers have no impacts. By law, there must be a buyback center within 0.5 miles of every supermarket in the state. We assume that a consumer travels to a buyback center upon collecting 1 kg of postconsumer bottles (roughly one grocery bag full of bottles), that travel to the buyback center involves 1.6 km round-trip travel in a U.S.-average vehicle, and that 25 percent of the trip is allocated to recycling return.

Buyback center trip distance (km):	**1.6**	DQI C
Buyback center allocation:	**0.25**	

Source separated processor, 1 kg post-consumer PET

Unlike MRFs, source-separated processors do not need to operate automatic machinery to sort their recyclate. Instead, they must operate a facility which requires electricity and propane. Data for source-separated processors was provided by four survey respondents.

Electric power required (MJ/kg):	**0.0046**	DQI D
LP Gas required (liter/kg)[4]:	**0.00106**	DQI D
Baling service required (kg/kg)[5]:	**1**	

4 The infrastructure model does not include a process inventory for combustion of propane in equipment. Combustion of LP gas in a boiler was used instead.

5 Each kg of PET that passes through a processor is assumed to be baled. Baling is modeled as a process which requires baling wire and electricity and provides the baling service. See the description of "PET baling, 1kg post-consumer PET," p. 38, for more information.

PET baling, 1 kg post-consumer PET

Polyethylene terephthalate (PET) bottles must be crushed into bales and bound with steel (or, infrequently, plastic) wire for transportation from the processor to the reclaimer. Specifications for best practices in PET baling can be found on the Internet.[6] Here we model baling as a unit process which requires baling wire and electricity and converts 1 kg loose PET into 1 kg baled PET. Baling is performed by both materials recovery facilities (MRFs) and source-separated processors. Electric power requirements were estimated based on a review of baling machine product literature and specifications.

Bale recommended density (lb/ft3):	**18**	
Bale recommended volume (ft3):	**50** (representing 60"x30"x48" bale)	
Baling wire, 10AWG, required per bale (m):	**17**	DQI B
Baling wire required per kg PET (m): 0.039		
Electric power required (MJ/bale):	**0.48**	DQI C
Electric power required per kg PET (MJ): 0.0012		

Brokerage of PET

Postconsumer processors must sell their bales to reclaimers at market rates. Brokerage of PET is modeled as a distribution process which apportions baled PET among California reclaimers, out-of-state U.S. reclaimers, and foreign reclaimers in the Far East. No impacts are incurred in this process. (see rPET Logistics, below; see also Scenario Parameters, below).

4.3.4 Reclamation

rPET Logistics

This process includes freight for transporting bales of post-consumer PET from processors to reclaimers. Distances are estimates. Train fraction comes from Oregon Department of Environmental Quality (DEQ) report.

Distance from processor to in-state reclaimer in CA (km):	**250**	DQI C
Distance from processor to out-of-state reclaimer in US (km):	**3500**	DQI C
Train fraction of out-of-state freight:	**0.2**	DQI B
Distance from processor to Pacific port (km):	**100**	DQI C
Distance from California port to foreign port (km):	**10000**	DQI D

6 See, for instance, http://www.prcc.biz/guidlines.html and http://www.plasticsrecycling.org/technical_resources/model_bale_specifications/pet.asp#prohibited2

Reclamation, 1 kg Baled PET

The process of polyethylene terephthalate (PET) reclamation was recently characterized by Franklin Associates in a report for the American Chemistry Council and the Association for Postconsumer Plastic Recyclers (Franklin Associates, 2010). According to the FAL model, PET is washed in a caustic bath with sodium hydroxide (NaOH). According to our research, the wash water is treated with aluminum chloride (AlCl3), which reacts with NaOH to form aluminum oxide sludge (Al(OH)3) and NaCl. The aluminum oxide is recovered and can be sold or disposed as hazardous waste.

Electric power required (MJ/kg):	**1.32**	DQI B
Natural gas for thermal energy (m3/kg):	**0.0603**	DQI B
Wash water (kg/kg):	**0.32**[7]	DQI D
Reclamation yield:	**0.8**	DQI B
Waste to landfill (kg/kg):	**0.176**[8]	DQI B
LP Gas combusted (liter/kg): (see note 4, p.37)	**0.00030**	DQI B
Sodium Hydroxide required (kg/kg; 50 percent solution):	**0.0381**	DQI B

Other inputs omitted from model:

Surfactants, Defoamers, Wetting Agents, Aluminum Chloride.

rPET Disposition

This is a distribution process which apportions the rPET produced into three categories: U.S. food-grade use, U.S. non-food-grade use, and foreign use. The proportion of food-grade U.S. to total U.S. rPET production is taken to be equal to the proportion of reclamation facilities which possess FDA Letters of Non-Objection (LNO), as reported by the National Association for PET Container Resources (NAPCOR). (see Scenario Parameters, below).

4.3.5 Support

Distribution, Diesel Fuel from Refinery to Filling Station

This distance is based on data from the 2002 Commodity Flow Survey for average shipment distance, category 180, Fuel Oils, U.S. average.

Distance, diesel refinery to filling station (km):	**52**	DQI A

7 A model for polyethylene reclamation developed for a prior study indicated 2.2 kg water/kg plastic; information from a reclaimer operating in California indicated the use of 4.3 kg water/kg plastic. The 0.32 kg water/kg plastic figure reported by FAL is thus surprisingly low.

8 The remaining 0.024 kg/kg represents olefins recovered for reuse.

Distribution, Gasoline from Refinery to Filling Station

This distance is based on data from the 2002 Commodity Flow Survey for average shipment distance, category 171, Gasoline, U.S. average.

Distance, gasoline refinery to filling station (km):	**82**	DQI A

Transport, Medium-heavy duty single unit truck

Transport, Combination Truck

The U.S. LCI database includes processes for transport of freight by truck. However, these models are based on the GREET model of passenger vehicle transportation published by Argonne National Lab. GREET does not include data for freight transport, and the values in the U.S. LCI database are developed from assumptions by Franklin Associates personnel. We developed an independent model of truck transportation based on the data contained in the EMFAC model published by the California Air Resources Board. Our methodology for developing this process inventory, as well as the resulting emission factors, are discussed in Appendix B. Here we report only fuel usage.

Diesel fuel required, Light-heavy duty truck or Volume-limited medium-heavy duty truck (kg/tkm):	**0.1096**	DQI C
Diesel fuel required, Medium-heavy duty truck (kg/tkm):	**0.0789**	DQI C
Diesel fuel required, Combination truck (kg/tkm):	**0.0369**	DQI B

4.4 Logistical Parameters used in Scenario Modeling

The below parameters describe the flow of materials in the polyethylene terephthalate (PET) life cycle.

Parameter	2009 Baseline	Alt. (CA)	BW Variant	CSD Variant	Source
Volume of beverage delivered (L):	**27.9**	-	1000	1000	
Mass of PET per container (g):	**18.6**	-	12.8	23.9	Measurement
Mass of PP per container (g):	**2.7**	-	2.0	2.9	Measurement
Fraction of secondary PET in bottles:	**0.039**	0.15	-	-	NAPCOR
Distance: PET resin, factory to bottler (km):	**3500**	-	-	-	SRI
Distance: PP, factory to bottler (km):	**3500**	-	-	-	--
Distance: In-state reclaimer to bottler (km):	**500**	-	-	-	--
PET bottle collection rate:	**0.73**	-	-	-	DOR
Residential curbside fraction:	**0.15**	-	-	-	DOR
Buyback center fraction:	**0.76**	-	-	-	DOR
Distance from recycler to local processor (km):	**30.4**	-	**-**	**-**	Appendix A
Distance to out-of-county processor (km):	**348**	-	-	-	Appendix A
Remote fraction of commingled plastic:	**0.307**	-	**-**	**-**	Appendix A
Remote fraction of source-separated plastic:	**0.307**	-	-	-	Appendix A
Fraction of CA postconsumer PET exported:	**0.75**	0	-	-	DOR 2007
Fraction of CA postconsumer PET in-state:	**0.08**	1	-	-	DOR 2007
Food-grade (LNO) fraction of U.S. reclaimers:	**0.54**	1	-	-	NAPCOR

Note: A dash (-) indicates that the parameter retains the Base value in a given scenario.

Sources:

DOR—Refers to a database of county-by-county collection and processing volumes for the years 2001-2007, provided to us by DOR personnel in Fall 2008.

NAPCOR—Refers to a set of annual reports published by the National Association for PET Container Resources.

SRI—Refers to a trade report published by SRI Consulting as part of the Chemical Economics Handbook; purchased by the authors.

Appendix A—Refers to the model of postconsumer PET logistics developed for this research, described in Appendix A of this report.

DOR 2007—Refers to the “Market Analysis for Recycled Beverage Container Materials: 2007 Update” prepared by the NewPoint Group for the California Department of Conservation.

5 Life Cycle Inventory Results

The inventory indicator results from our model are shown in Figures 3.1-3.4 and Tables 3.1-3.7. The base case models the delivery of beverages resulting from the production of 1 kg of primary polyethylene terephthalate (PET) resin. Food and beverage bottles are assumed to have an average recycled content of 3.9 percent, which was the approximate value in the 2009 study year (NAPCOR, 2010). The base case resulted in the co-production of 0.55 kg secondary PET, as well as 0.018 kg of other secondary plastics and 7.2 grams of aluminum hydroxide waste per kg of PET resin input. The burdens of producing this secondary material are counted in full in the current model.

Table 3.1 PET Bottle—Complete Life Cycle

	2009 Baseline	California Scenario (CA)	BW Variant	CSD Variant
Products				
Beverage Delivered [L]	27.9	27.9	1000.	1000.
Secondary PET (Open-loop recycled) [kg]	0.547	0.436	14.51	22.50
Secondary Mixed Plastic Waste [kg]	0.018	0.018	0.47	0.72
Aluminum Hydroxide [kg]	0.0072	0.0072	0.19	0.29
Inventory Indicators				
Gross Primary Energy Demand [MJ]	128.6	117.9	3464	5155
Net Primary Energy Demand [MJ]	119.6	109.7	3222	4796
Gross Feedstock Energy [MJ]	48.1	43.7	1278	1922
Net Feedstock Energy [MJ]	44.3	40.2	1178	1773
Net Delivered Energy [MJ]	47.8	43.3	1299	1917
Freight Services Provided [tkm]	20.52	13.53	565.3	825.2
Net Transport Energy [MJ]	14.3	12.0	408.1	564.8
Waste Disposal Provided [kg]	0.73	0.71	19.3	29.1

Figure 3.2 details the delivery of energy to the product system. The product system required 119.6 MJ of primary energy (PE) (all results in the text are given in terms of net calorific value). This is roughly equal to the energy of one U.S. gallon of gas. Of that amount, 44.3 MJ (37 percent) represents the energy of PET and polypropylene (PP) feedstocks, 47.8 MJ (40 percent) is delivered to processes and the remaining 27.5 MJ is lost. This loss figure does not include the amount of feedstock energy lost to landfill when bottles are thrown away. The efficiency of the energy delivery infrastructure can be expressed as (DE / (PE - FE)) - the ratio of energy delivered to non-feedstock energy consumed - which is 63.5 percent for the baseline system.

Polymer production and beverage manufacturing together accounted for 85 percent of delivered energy. Combustion of natural gas for energy in the polymer production phase is the process with the single greatest energy requirements, at 24 percent of delivered energy. It is followed by electricity production for injection stretch blow molding of bottles (14 percent). Production of

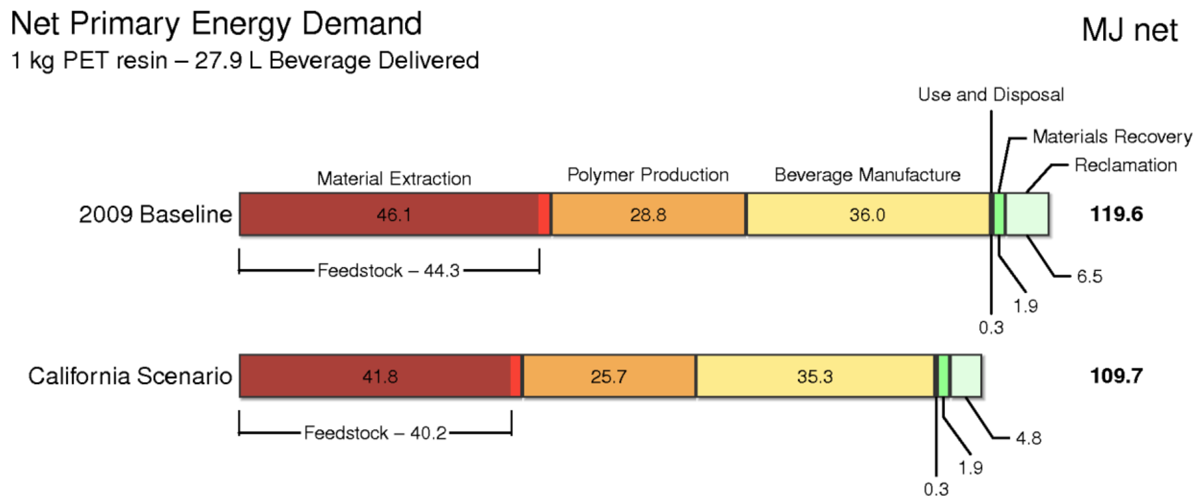


Figure 3.1 Net Primary Energy Demand of the baseline system and California alternative scenario. Feedstock energy is the energy content of oil and gas contained in the polymer.

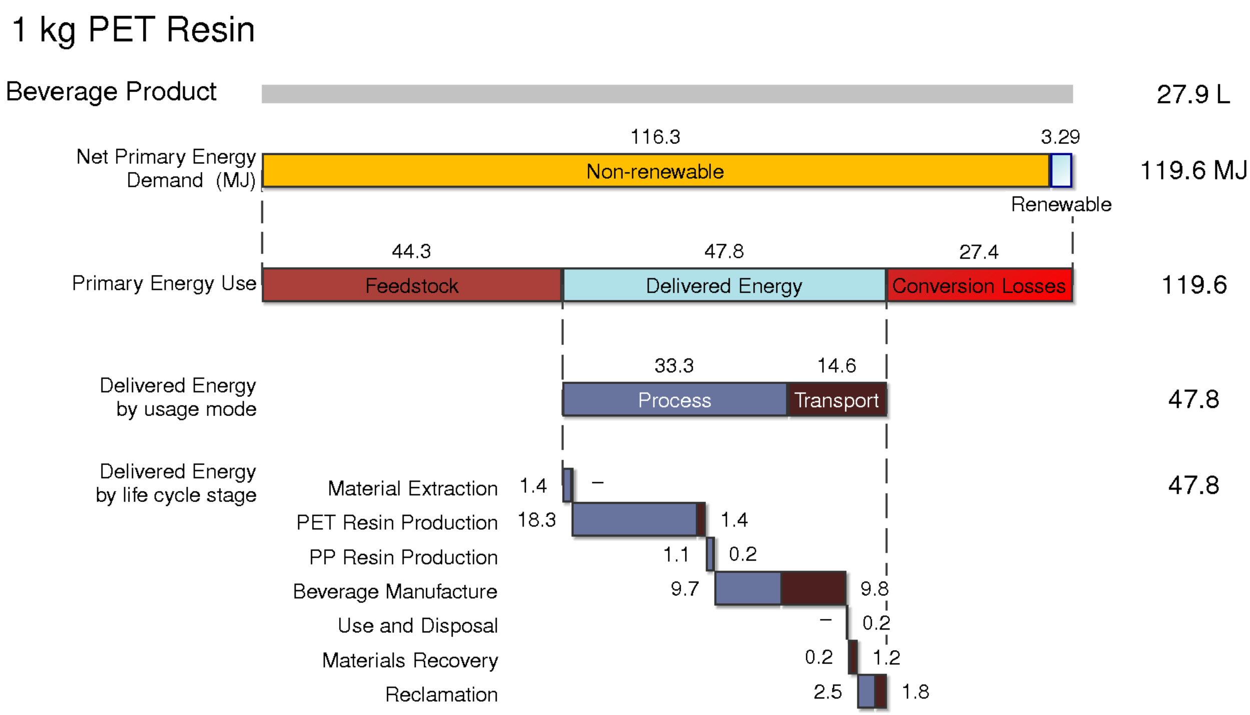


Figure 3.2 Detail of energy usage in the product system (2009 Baseline). Feedstock energy is not used to perform work. Delivered energy is energy provided to transformation processes or used in transport. Conversion losses represent the energy used in the fuel production cycle, as well as waste heat from the conversion of fossil fuels into electricity.

Delivered energy is shown broken down by usage mode (to process / to transport) and by life cycle stage. For each stage, the energy used in process (blue) and in transport (dark red/gray) is indicated.

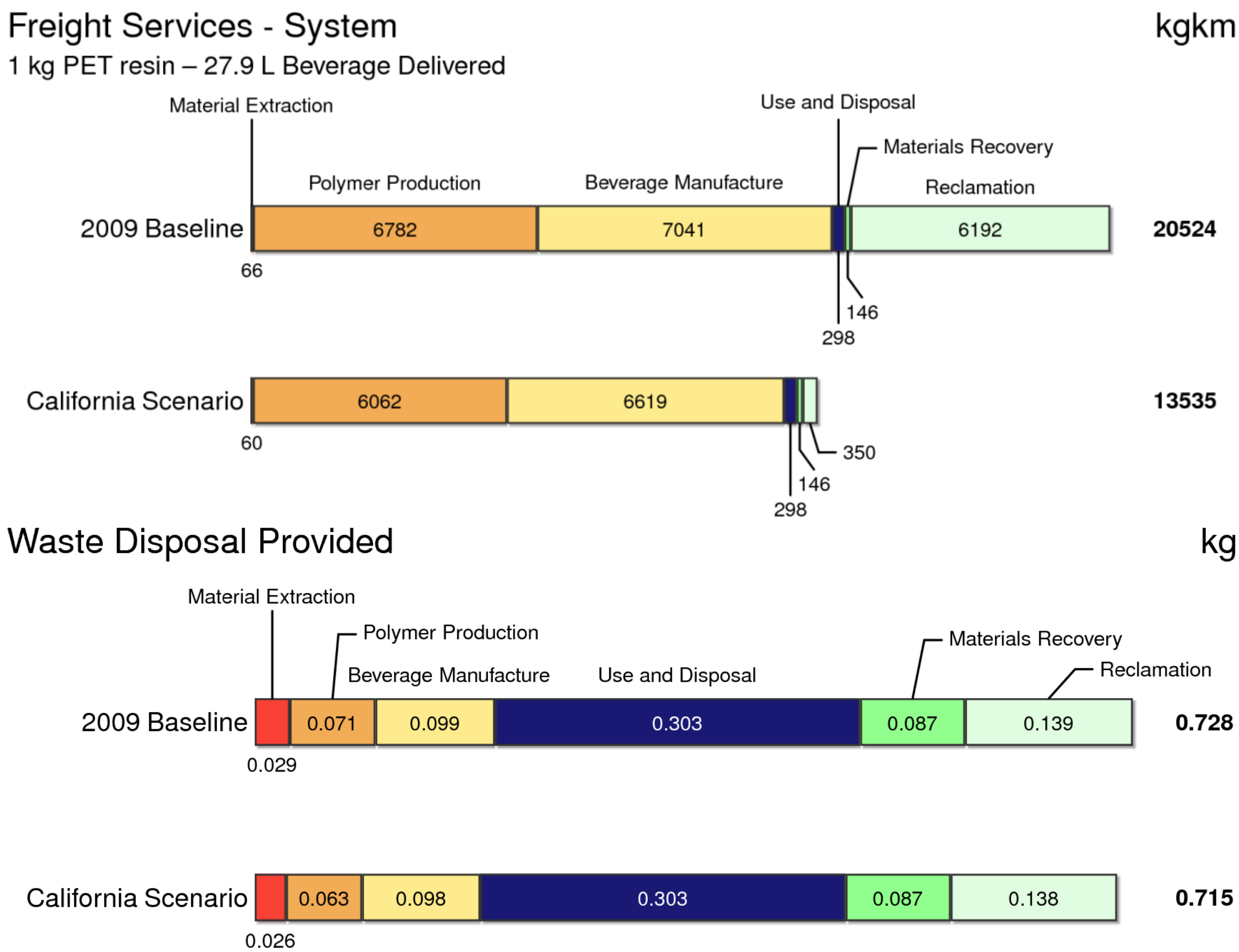


Figure 3.3 Freight services and waste disposal inventory indicators for both scenarios. These figures show the total amount of each service required cumulatively by the product and upstream supply chain.

secondary polyethylene terephthalate (PET) generates 14.3 MJ of primary energy demand per 1 kg of secondary PET produced, measured from disposal to reclaimer gate.

The Primary Energy Demand of the materials recovery life cycle stage totaled only 2.56 MJ per kg PET recycled (1.9 MJ per 2009 baseline functional unit), including consumer dropoff, curbside collection, and transport from collection to processing. Materials recovery accounted for only 146 kg·km of freight per functional unit, or 0.6 percent of the total. Recycled PET traveled an average 132 km between disposal and recovery (see Appendix A).

Freight services totaled 20,500 kg·km per kg of PET resin, requiring 14.6 MJ of transportation energy (TE), including the product system and supply chain requirements. This represents 30 percent of delivered energy. Beverage manufacture and distribution accounted for 37.5 percent of life cycle freight services and 72 percent of life cycle transportation energy.

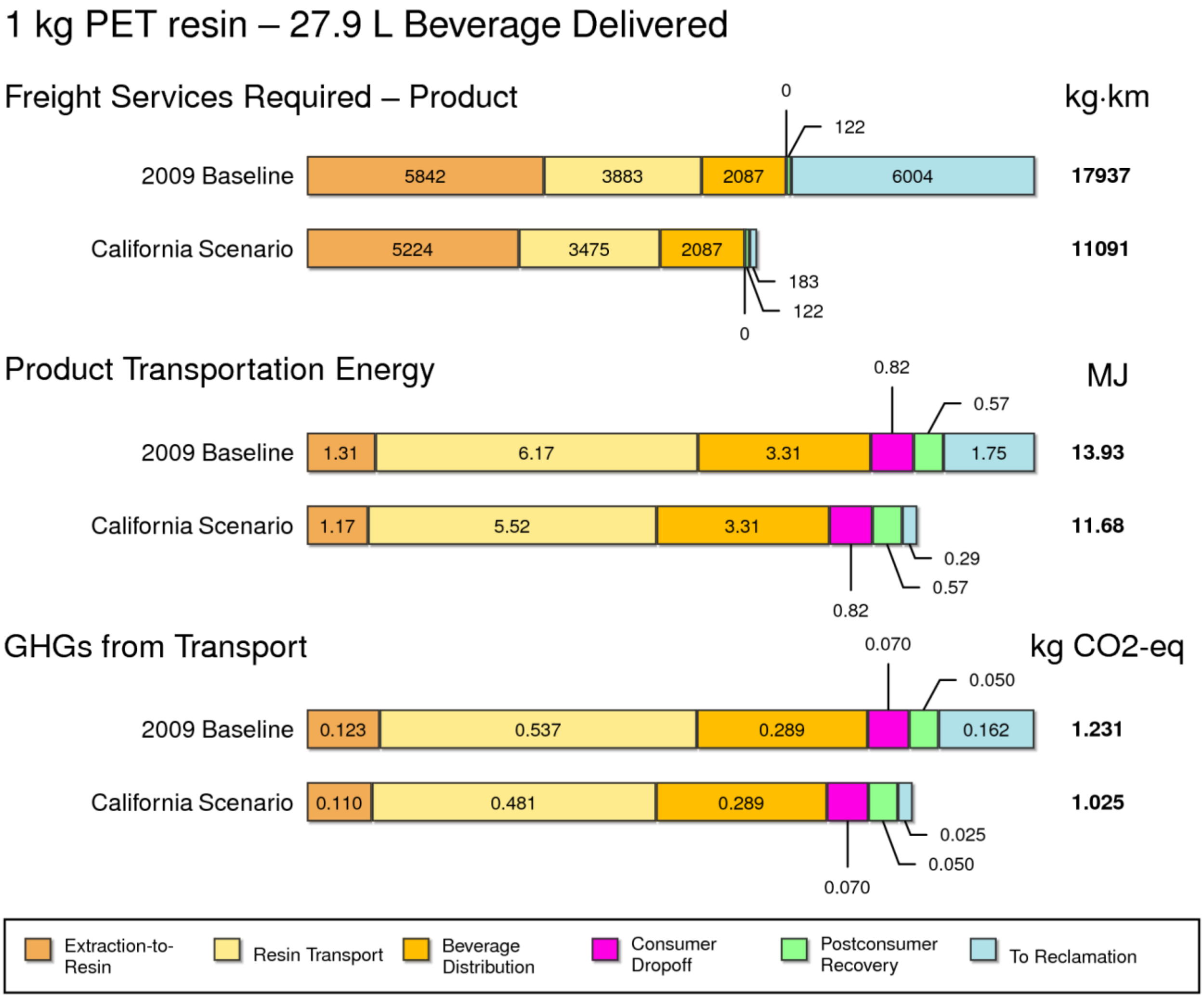


Figure 3.4 Transportation-related indicators for the 2009 baseline and California scenario, by transportation step. This figure includes transport of the product system only (freight services required upstream in the supply chain and for the fuel production cycle are excluded).

Unsurprisingly, disposal of non-recycled polyethylene terephthalate (PET) bottles themselves accounted for the largest share of waste disposal services (42 percent), with the remainder evenly split between pre-consumer and post-consumer stages. Most of the pre-consumer waste is associated with energy production, while most of the post-consumer waste represents yield losses in the reclamation process and disposal of the portion of caps and labels that are not recycled.

Freight services required by the product system are displayed in Figure 3.4. Transporting components of the product system itself accounted for 17,900 kg·km; required 13.9 MJ of transportation fuel (12 percent of total); and resulted in the release of 1.23 kg CO_2-eq of greenhouse gases (21 percent of total). Consumer travel to drop-off locations makes a significant contribution to transportation energy and greenhouse gas emissions because of the relative inefficiency of personal transport. These results are strongly dependent on the choice of allocation methods (see Section 2.3.3).

5.1 California Scenario

There are two principal differences in the California scenario in comparison to the baseline: freight of post-consumer bottles to reclamation is greatly reduced; and there is a small (12 percent) reduction in the demand for primary PET due to increased recycled content. Beverage manufacture, distribution, use and disposal, and materials recovery are essentially unchanged between the two scenarios, and consequently the scope of possible improvement in inventory indicators is small.

The California scenario results in a substantial (40 percent) reduction in total freight requirements, but most of that reduction comes from energy-efficient ocean freight, so reductions in transport-related energy and emissions are more modest. Waste disposal is unaffected, though more waste would be disposed within the state of California.

5.2 Inventory Requirements by Volume

The two variants of the baseline scenarios represented delivery of 1,000 L of two different product sub-systems, bottled water (BW) and carbonated soft drinks (CSD). These scenarios differed from the base case solely in the quantity of PET and PP resins required.

The bottled water system required 25.16 kg primary PET and 4.03 kg PP per 1,000 L of beverage, and produced 14.5 kg of secondary PET, 0.47 kg of other secondary plastics, and 0.19 kg of aluminum hydroxide. The bottled water system exhibited a total primary energy demand of 3,220 MJ and required 565 t·km of freight services.

The carbonated soft drink system required 39.7 kg primary PET and 4.94 kg PP per 1,000 L of

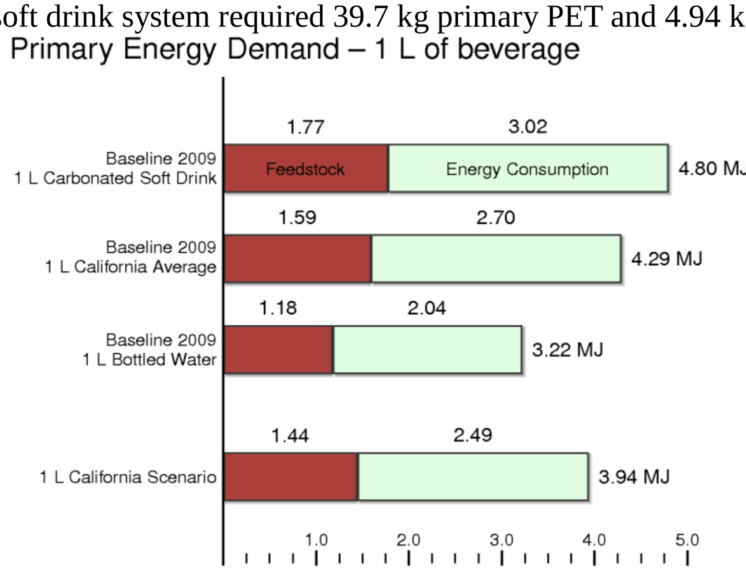


Figure 3.5 Primary energy requirements per unit of volume delivered by the product system.

beverage, and produced 22.5 kg of secondary polyethylene terephthalate (PET), 0.72 kg of other secondary plastics, and 0.29 kg aluminum hydroxide. This system exhibited a total primary energy demand of 4,800 MJ and required 825 t·km of freight services. The energy requirements are summarized on a per-liter basis in Figure 3.5.

5.3 Process Inventory Details by Life Cycle Stage

Below is a list of basic processes included in each life cycle stage. Each process is named and its source identified in parentheses. Processes which were modeled by us (source listed as "Bren") are described above in section 2.3, "Details about Custom-Modeled Processes."

5.3.1 Fossil Feedstock Extraction

Table 3.2 Fossil Feedstock Extraction life cycle stage—Aggregate results

	2009 Baseline	Alt. (CA)	BW Variant	CSD Variant
Products				
Crude Oil for Feedstock [kg]	0.645	0.577	17.00	26.31
Natural Gas for Feedstock [kg]	0.389	0.361	10.48	15.09
Inventory Indicators				
Gross Primary Energy Demand [MJ]	50.0	45.4	1329	1998
Net Primary Energy Demand [MJ]	46.1	41.8	1225	1843
Gross Feedstock Energy [MJ]	48.0	43.6	1276	1919
Net Feedstock Energy [MJ]	44.3	40.2	1176	1770
Net Delivered Energy [MJ]	1.4	1.3	37	56
Freight Services Provided [tkm]	0.07	0.06	1.7	2.6
Net Transport Energy [MJ]	0.0	0.0	0.5	0.7
Waste Disposal Provided [kg]	0.03	0.03	0.8	1.2

Fossil fuel extraction is part of the core infrastructure database.

5.3.2 Resin Production

All basic processes in the resin production life cycle stage are taken from the U.S. LCI database.

Table 3.3 Polymer Production life cycle stage—Aggregate results

	2009 Baseline	Alt. (CA)	BW Variant	CSD Variant
Products				
PET Resin [kg]	0.961	0.850	25.16	39.74
PP Resin [kg]	0.143	0.143	4.03	4.94
Inventory Indicators				
Gross Primary Energy Demand [MJ]	31.1	27.7	818	1275
Net Primary Energy Demand [MJ]	28.8	25.7	757	1180
Gross Feedstock Energy [MJ]	0.0	0.0	0	0
Net Feedstock Energy [MJ]	0.0	0.0	0	0
Net Delivered Energy [MJ]	21.0	18.7	552	859
Freight Services Provided [tkm]	6.78	6.06	178.6	276.7
Net Transport Energy [MJ]	1.6	1.4	41.4	63.8
Waste Disposal Provided [kg]	0.07	0.06	1.9	2.9

PET Resin Production (U.S. LCI) - Gate-to-Gate Process

- Petroleum refining coproduct, unspecified, at refinery[9]
- Xylenes, mixed, at plant;
- Paraxylene, at plant;
- Natural gas, processed, at plant;
- ethylene production;
- oxygen, liquid, at plant;
- ethylene oxide, at plant;
- acetic acid, at plant (for DMT route);
- methanol, at plant (for DMT route);
- Polyethylene terephthalate resin, at plant.

Inputs:

0.614 kg Crude Oil
0.251 kg Natural Gas

Outputs:

1 kg PET Resin
1.07 MJ Recovered Energy

[9] No U.S. LCI process was available for "Petroleum refining coproduct, unspecified." We used “Petroleum refining coproduct, for olefins production” instead.

Support Processes Required:

Coal, combusted	0.036	kg
Diesel fuel	1.28E-05	kg
PET to Incineration	0.0016	kg
PET to Landfill	0.012	kg
Electricity, Cogenerated	0.23	MJ
Electricity – U.S. Grid	3.05	MJ
Gasoline, combusted	2.90E-08	m3
LP Gas, combusted	5.59E-06	m3
Natural gas, combusted	0.32	m3
Fuel oil, combusted	7.70E-05	m3
Transport, Barge	0.14	tkm
Transport, Heavy Truck	0.03	tkm
Transport, Ocean	2.81	tkm
Natural Gas Pipeline	0.33	tkm
Petroleum Pipeline	0.62	tkm
Transport, Train	1.63	tkm

PP Resin Production (U.S. LCI) - Gate-to-Gate Process

- Petroleum refining coproduct, for olefins production, at refinery;
- Natural gas, processed, for olefins production, at plant;
- Propylene production;
- Polypropylene resin, at plant.

Inputs:

Crude Oil	0.388 kg
Natural Gas	1.033 kg

Outputs:

PP Resin	1 kg
Recovered Energy	7.35 MJ

Support Processes Required:

Diesel, combusted	5.65E-08	m3
PP to Incineration	0.0076	kg
PP to Landfill	0.0025	kg
Refinery Sludge	2.81E-05	kg
Electricity, Cogenerated	0.71	MJ
Electricity – U.S. Grid	1.2	MJ
Gasoline, combusted	5.69E-08	m3
LP Gas, combusted	3.45E-07	m3
Natural gas, combusted	0.16	m3
Fuel oil, combusted	1.26E-05	m3
Transport, Barge	0.08	tkm
Transport, Heavy Truck	0.03	tkm
Transport, Ocean	1.75	tkm
Natural Gas Pipeline	1.15	tkm
Petroleum Pipeline	0.41	tkm
Transport, Train	0.02	tkm

5.3.3 Beverage Manufacturing Stage

Table 3.4 Beverage Manufacture and Distribution life cycle stage—Aggregate results

	2009 Baseline	Alt. (CA)	BW Variant	CSD Variant
Products				
Beverage Delivered [L]	27.9	27.9	1000.	1000.
Inventory Indicators				
Gross Primary Energy Demand [MJ]	38.2	37.4	1067	1505
Net Primary Energy Demand [MJ]	36.0	35.3	1007	1420
Gross Feedstock Energy [MJ]	0.1	0.1	2	3
Net Feedstock Energy [MJ]	0.1	0.1	2	3
Net Delivered Energy [MJ]	19.5	18.8	552	761
Freight Services Provided [tkm]	7.04	6.62	206.4	274.7
Net Transport Energy [MJ]	9.8	9.1	288.6	380.3
Waste Disposal Provided [kg]	0.10	0.10	2.7	4.0

Beverage Manufacture - Gate-to-gate Process

- Extrusion, LDPE film (Bren);
- Injection molding, PP compound (Bren);
- Stretch blow molding (Bren);
- Beverage assembly (Bren);
- Beverage distribution (Bren).

Inputs:		Base	CA	BW	CSD
PP Resin	kg	5.131	5.131	4.030	4.942
PET Resin	kg	35.02	30.50	25.55	40.36
R-PET	kg	0.861	5.383	0.628	0.992

Outputs:		Base	CA	BW	CSD
Beverage Product	L	1000	1000	1000	1000

Support processes required:

		Base	CA	BW	CSD
PET to Landfill	kg	0.789	0.789	0.576	0.909
PP to Landfill	kg	0.0365	0.0365	0.0303	0.0348
Electricity - WECC	MJ	297.2	297.2	225.7	331.6
Gasoline, combusted	m3	1.15E-04	1.15E-04	8.33E-05	1.13E-04
LP Gas, combusted	m3	3.96E-06	3.96E-06	2.86E-06	3.87E-06
Natural gas, combusted	m3	1.574	1.574	1.165	1.533
Fuel oil, combusted	m3	5.24E-05	5.24E-05	4.34E-05	4.99E-05
Transport, Heavy Truck	tkm	218.4	200.5	179.9	237.3
Lubricating Oil	kg	0.0707	0.0707	0.0517	0.0814

5.3.4 Use and Disposal

Table 3.5 Use and Disposal life cycle stage - Aggregate results

	2009 Baseline	Alt. (CA)	BW Variant	CSD Variant
Products				
PET Bottle, at disposal in Recycling [kg]	0.818	0.818	21.61	33.10
Inventory Indicators				
Gross Primary Energy Demand [MJ]	0.35	0.35	9.3	14.2
Net Primary Energy Demand [MJ]	0.33	0.33	8.7	13.3
Gross Feedstock Energy [MJ]	0.0	0.0	0	0
Net Feedstock Energy [MJ]	0.0	0.0	0	0
Net Delivered Energy [MJ]	0.20	0.20	5.3	8.1
Freight Services Provided [tkm] [10]	0.30	0.30	10.51	10.78
Net Transport Energy [MJ]	0.07	0.07	1.9	2.9
Waste Disposal Provided [kg]	0.30	0.30	8.0	12.3

Use and Disposal:

- Dummy use phase;
  (Process apportions end of life bottles between landfill and recycling)
- Municipal waste collection (Bren).

Inputs:

		Base / CA	BW	CSD
Beverage Product	L	1000	1000	1000

Outputs:

		Base / CA	BW	CSD
PET Bottle, Recycled	kg	29.3	16.0	24.5

Support processes required:

		Base / CA	BW	CSD
Diesel fuel	kg	0.107	0.135	0.206
PET to Landfill	kg	10.9	13.62	20.9
Transport, Truck	tkm	0.542	0.681	1.043

[10] Note that freight services are provided by the product system during use. These amount to 0.279 tkm in the base case and California scenarios, and 10.0 tkm in the bottled water and carbonated soda variants.

5.3.5 Materials Recovery

Table 3.6 Materials Recovery life cycle stage—Aggregate results

	2009 Baseline	Alt. (CA)	BW Variant	CSD Variant
Products				
PET, Baled at processing facility [kg]	0.733	0.733	19.42	30.14
Inventory Indicators				
Gross Primary Energy Demand [MJ]	2.00	2.00	57	78
Net Primary Energy Demand [MJ]	1.88	1.88	54	73
Gross Feedstock Energy [MJ]	0.0	0.0	0	0
Net Feedstock Energy [MJ]	0.0	0.0	0	0
Net Delivered Energy [MJ]	1.39	1.39	38	55
Freight Services Provided [tkm]	0.146	0.146	4.01	5.81
Net Transport Energy [MJ]	1.06	1.06	28.0	42.8
Waste Disposal Provided [kg]	0.09	0.09	2.3	3.1

PET Recycling (Bren) - Gate-to-gate Process

- curbside collection (Bren);
- Materials recovery facility (Bren);
- Recycling buyback center (Bren);
- Source separated processor (Bren);
- PET baling (Bren);
- Brokerage of PET (Bren).

Inputs:

		Base / CA	BW	CSD
PET Bottle, Recycled	kg	1.115	1.113	1.098

Outputs:

1 kg PET, Baled

Support processes required:

		Base / CA	BW	CSD
Diesel fuel	kg	4.53E-03	4.52E-03	4.46E-03
PP to Landfill	kg	0.115	0.113	0.098
Electricity - WECC	MJ	0.200	0.280	0.160
Gasoline	kg	0.0254	0.0253	0.0250
LP Gas, combusted	m3	2.79E-06	2.78E-06	2.76E-06
Transport, Heavy Truck	tkm	0.119	0.119	0.117
Transport, Truck	tkm	0.026	0.026	0.026
Water	kg	0.037	0.037	0.026
Lubricating Oil	kg	2.68E-07	2.67E-07	2.64E-07
Baling Wire	kg	1.64E-03	1.64E-03	1.64E-03

5.3.6 Reclamation

Table 3.7 Reclamation life cycle stage—Aggregate results

	2009 Baseline	Alt. (CA)	BW Variant	CSD Variant
Products				
R-PET, to foreign market [kg]	0.440	0.000	11.65	18.08
R-PET, food-grade, to US non-bottle use [kg]	0.040	0.237	1.08	1.64
R-PET, to US non-food use [kg]	0.067	0.199	1.79	2.77
R-PET, food grade, closed-loop recycled [kg]	0.039	0.150	1.02	1.61
Secondary Mixed Plastic Waste [kg]	0.018	0.018	0.47	0.72
Aluminum Hydroxide [kg]	0.0072	0.0072	0.19	0.29
Inventory Indicators				
Gross Primary Energy Demand [MJ]	6.9	5.1	184	285
Net Primary Energy Demand [MJ]	6.5	4.8	171	266
Gross Feedstock Energy [MJ]	0.0	0.0	0	0
Net Feedstock Energy [MJ]	0.0	0.0	0	0
Net Delivered Energy [MJ]	4.3	2.8	114	177
Freight Services Provided [tkm]	6.19	0.35	164.0	254.5
Net Transport Energy [MJ]	1.8	0.3	47.8	74.2
Waste Disposal Provided [kg]	0.14	0.14	3.7	5.7

Reclamation (Bren) - Gate-to-gate Process

- rPET Logistics (Bren);
- Reclamation (Bren);
- rPET Disposition (Bren).

Inputs:

1 kg PET, Baled

Outputs:

0.072	kg R-PET, Food-grade
0.128	kg R-PET, Nonfood-grade
0.600	kg R-PET, foreign market
0.024	kg Plastic Waste for Recovery
0.010	kg Aluminum Hydroxide

Support processes required:

Mixed Plastics to Landfill	0.176	kg
Electricity - US Grid	1.32	MJ
LP Gas, combusted	2.42E-07	m3

Natural gas, combusted	0.060	m3
Transport, Heavy Truck	0.57	tkm
Transport, Ocean	7.5	tkm
Transport, Train	0.119	tkm
Water	0.320	kg
Waste Water Processing, organics	0.320	kg
Sodium Hydroxide	0.038	kg

6 Life Cycle Impact Assessment Results

Figures 4.1-4.4 show the results of impact assessment for the polyethylene terephthalate (PET) bottle life cycle and alternative California scenarios. The functional unit for all data presented here is 1 kg of polymer demand used to deliver 27.9 liters of California-average beverage. Figure 4.1 reports global warming potential for each life cycle stage. Figure 4.2 shows seven other environmental indicators relating to energy use and air and water quality. Figures 4.3 and 4.4 present toxicity impact indicators for the two scenarios. These results are discussed in-depth by life cycle stage in section 4.2. The tables in Appendix C report numerical results for all life cycle stages.

The data show that most environmental impacts are dominated by the energy-intensive polymer production and beverage manufacture stages. In five of eight categories, pre-consumer activity made up 80 percent or more of life cycle impact, due largely to energy production. The exceptions are eutrophication, which is dominated by the landfill component of the use and disposal phase, and ozone layer depletion potential. Regarding toxicity impacts, the results are more mixed. CML impact categories show a variety of contributions throughout the life cycle, though pre-consumer activity is heavily implicated. TRACI indicators suggest an increased significance of the reclamation stage, which dominates soil and water toxicity. Air toxicity is dominated by pre-consumer activity, again relating to energy production.

6.1 California Scenario

The California alternative scenario results in minor but significant reductions in several environmental impact categories related to air quality, including a 16 percent reduction in smog potential attributable to reduced ocean freight. Reductions in AP, GWP, POCP, and criteria pollutants are in line with the measured 9 percent reduction in primary energy demand in the

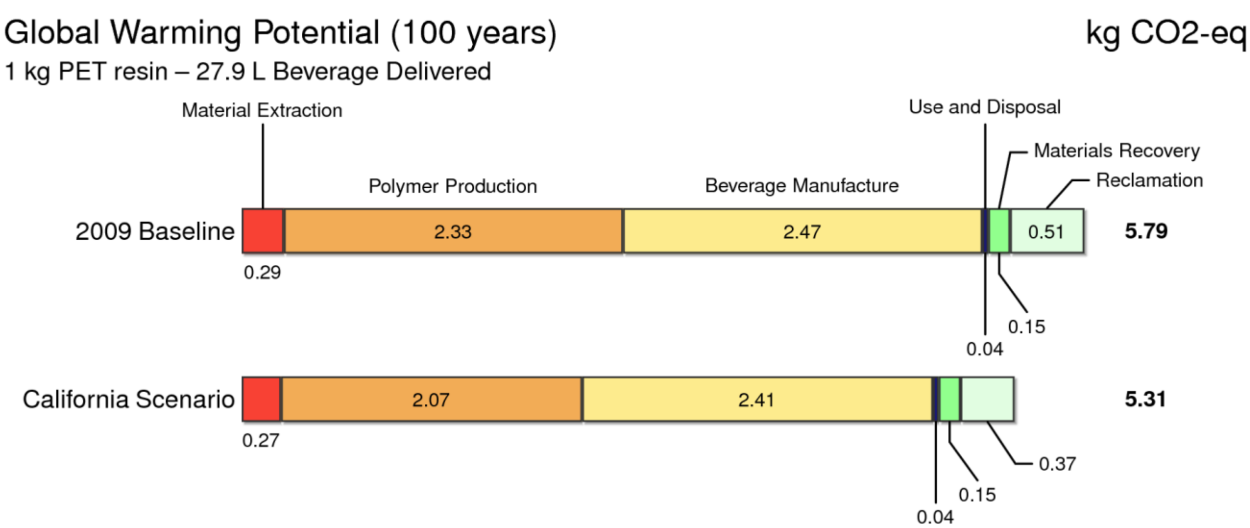


Figure 4.1 Life cycle impact assessment of global warming potential for 2009 baseline and California scenarios.

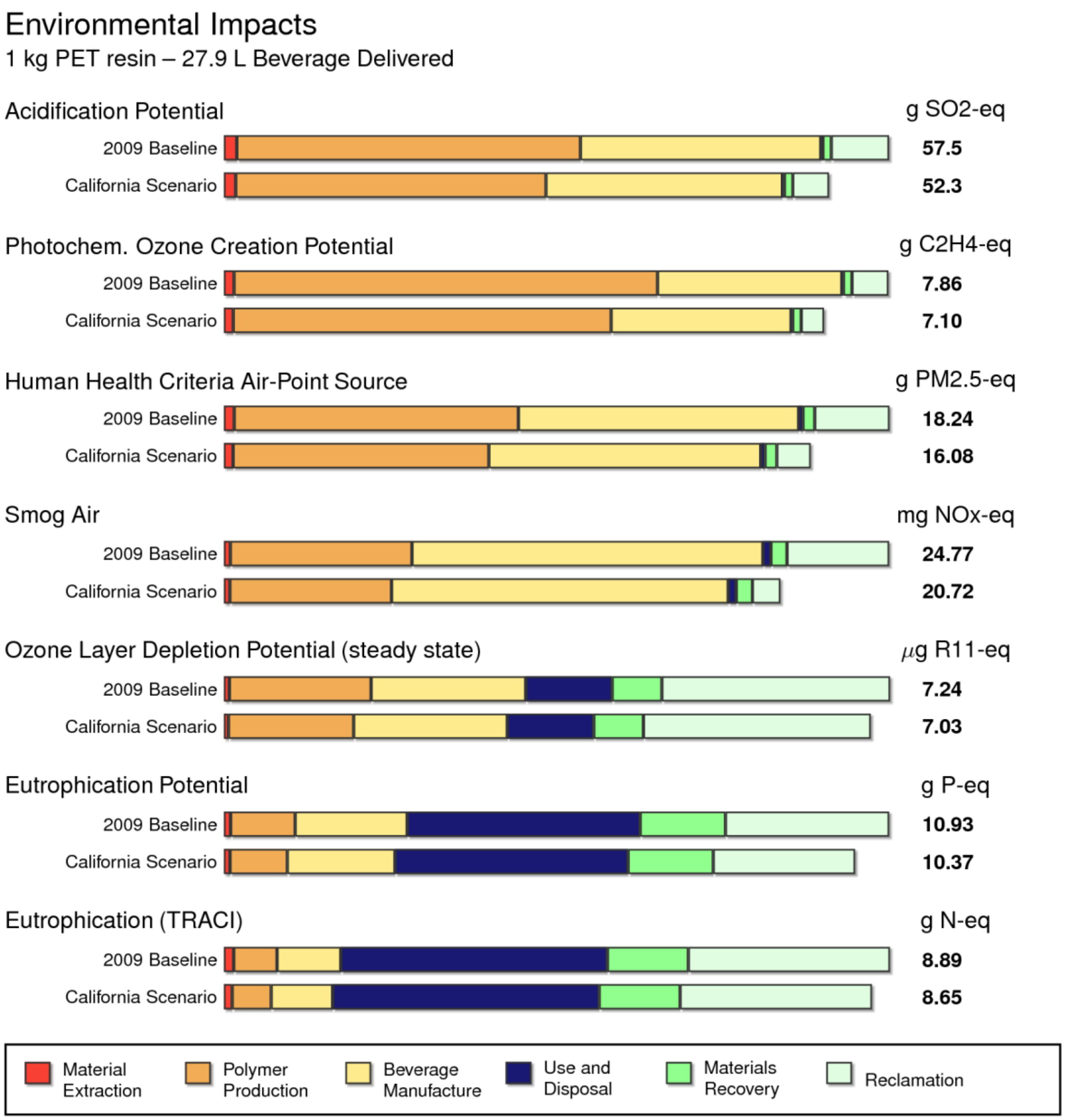


Figure 4.2 Seven other environmental impact indicators for 2009 Baseline and California scenarios. Numerical scores are tabulated by life cycle stage in Appendix C.

alternative scenario. Improvements in other categories are more modest or negligible.

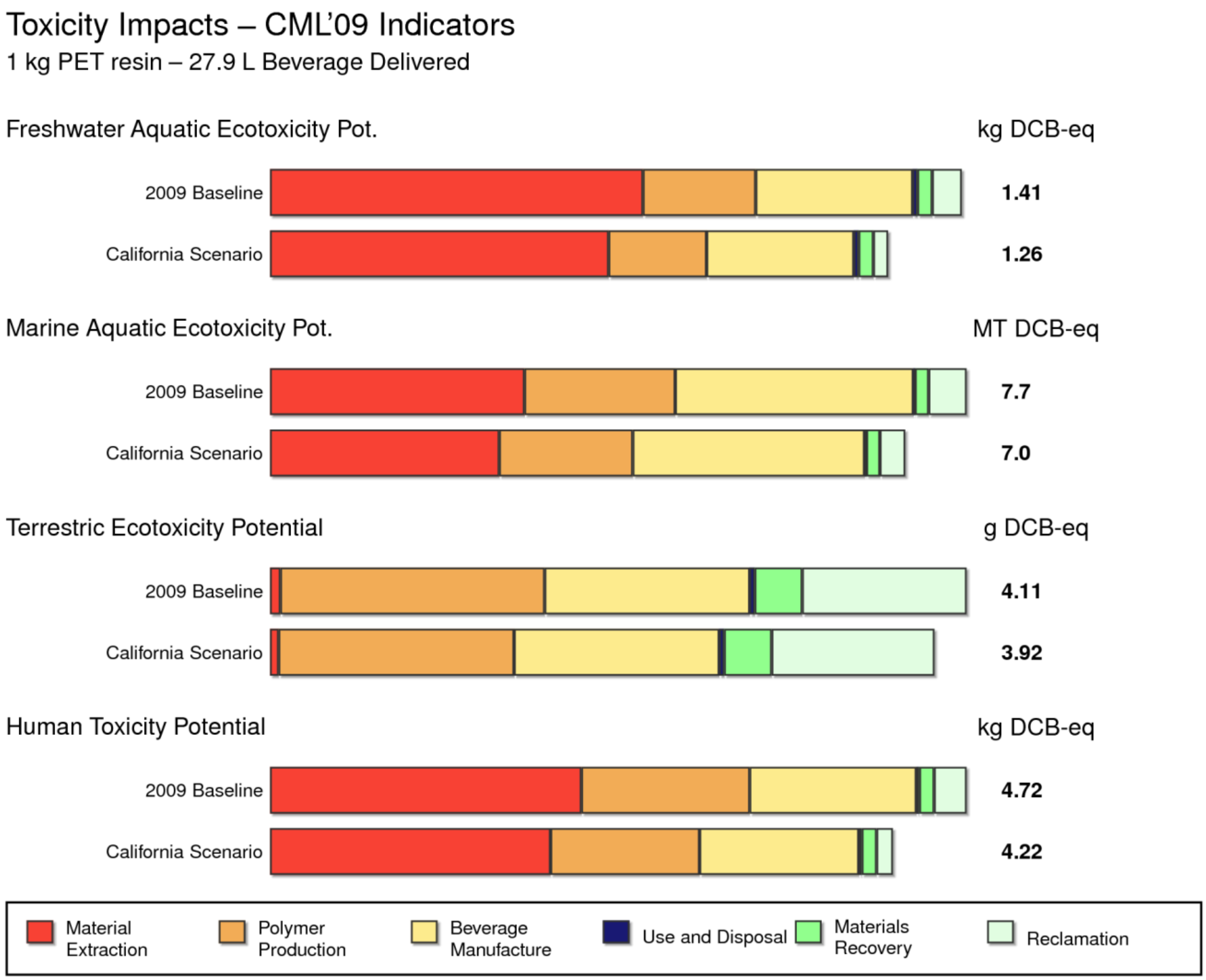


Figure 4.3 CML Toxicity indicators by life cycle stage for the two scenarios. Numerical scores are tabulated in Appendix C.

Improvements in CML toxicity categories are well correlated with the reduction in primary material demand resulting in the alternative scenario. Improvements in the TRACI scores in the alternative scenario are modest or negligible, except in cases where primary production stages are significant, namely toxic air emissions.

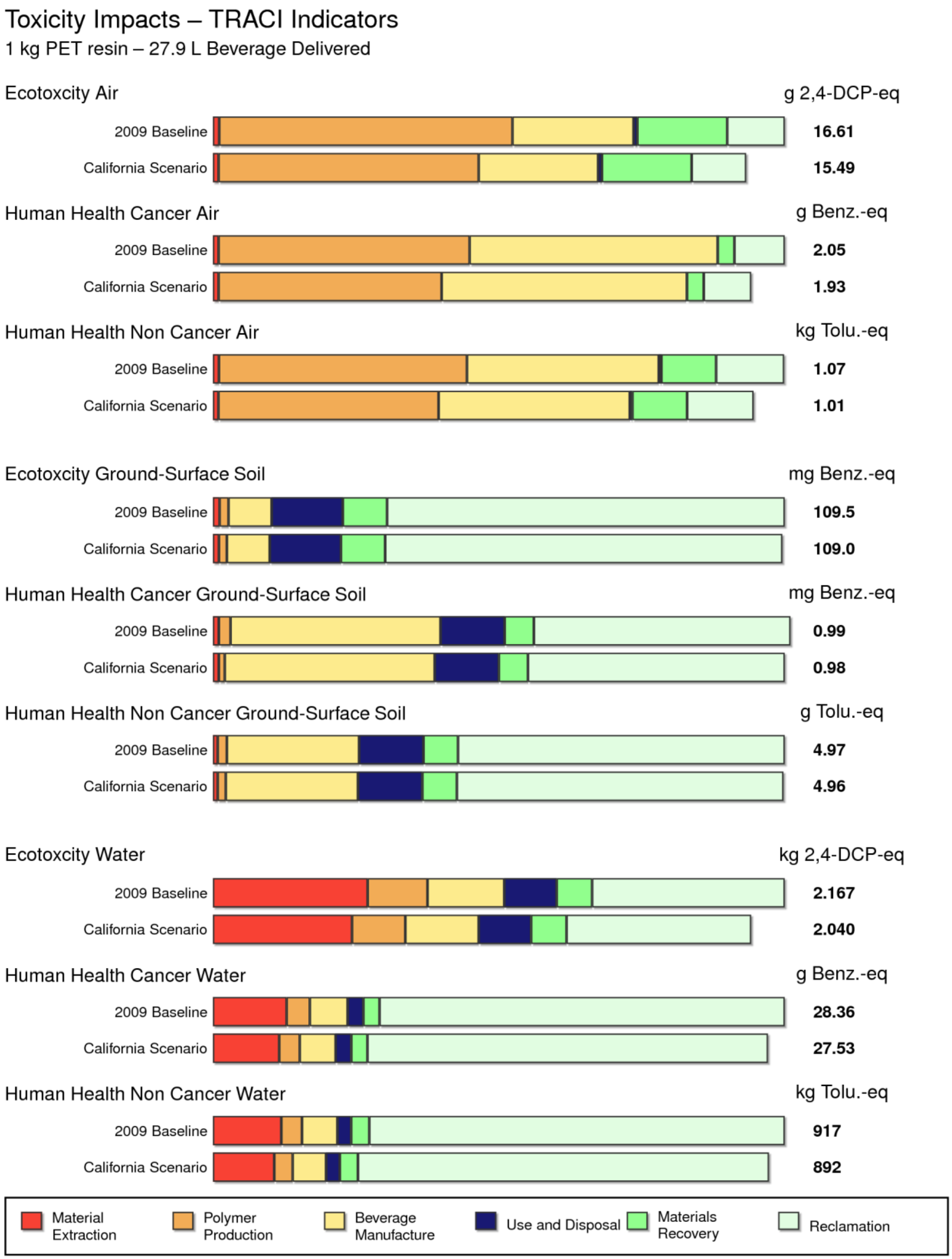


Figure 4.4 TRACI Toxicity indicators by life cycle stage for the two scenarios. Numerical results are tabulated in Appendix C.

6.2 Analysis of Impact Assessment Results

In this section we discuss the significant inventory flows and their impacts by life cycle stage.

6.2.1 Material Extraction

The extraction stage does not carry a significant share of impact in many categories. The exceptions are all toxicity-related. The eutrophication potential (CML) indicators show significant toxicity in freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), and human toxicity potential (HTP) categories; however, inspection of these impact shows that 96-99 percent of the impact is due to a single flow: the emission of barium to fresh water. Nickel is also significant to human toxicity, accounting for 3.4 percent of the HTP impact score.

The extraction stage also appears significant to TRACI impact categories for water media. However, in contrast with CML, barium does not appear in the TRACI toxicity scores. Instead, toxicity impacts are due to short-term and long-term emissions of lead (95-99 percent of both human health /cancer--water (HHC-W) and human health /non-cancer--water (HHNC-W) scores) and aluminum (+III ion, 75 percent of excotoxicity--water (ET-W) score). Again in contrast, lead makes a minuscule contribution to CML impact scores.

6.2.2 Polymer Production

Polymer production has significant impacts in nearly every impact category, but it is especially significant in the categories of acidification potential (AP), global warming potential (GWP), photo-oxidant creation potential (POCP), (TETP), excotoxicity –air (ET-A), human health/cancer—air (HHC-A), human health /non-cancer –air (HHNC-A), and human health/criteria pollutants/air (HH-Criteria), where it accounts for more than 40 percent of life cycle impacts. Its most substantial contribution is to POCP, where it contributes 64 percent of life cycle impacts, with two thirds of that amount coming from the polyethylene terephthalate (PET) polymer gate-to-gate process itself, largely from the emission of volatile organic chemicals. The gate-to-gate process also accounts for about a quarter of this stage's AP, HHC-A, and HH-Criteria scores, again in emissions of VOCs and particulates. Isoprene emissions from electricity production account for more than 90 percent of the smog score.

Toxicity scores reflect the emissions of heavy metals into the atmosphere. The TETP score is driven in large part by coal combustion, both for heat for the transformation process and in electricity production. Flows of mercury and chromium are implicated. Combustion of fuels, especially coal and heavy fuel oil, accounts for the high HHNC-A and ET-A scores, particularly in the form of emissions of lead and nickel to air. Arsenic makes up almost 70 percent of the HHC-A score, with VOC emissions from the gate-to-gate process making up much of the remainder.

6.2.3 Beverage Manufacture and Distribution

Beverage manufacturing accounts for around a third of life cycle impacts, with scores exceeding 30 percent of the life cycle total in the categories acidification potential (AP), global warming potential (GWP), eutrophication potential—air (EP-A), terrestric exotoxicity potential (TETP), human health/cancer—air (HHC-A), human health/cancer—ground/surface soil (HHC-GS), human health/criteria pollutants/air (HH-Criteria), human health /non-cancer –air (HHNC-A), and Smog and between 20-30 percent of the life cycle total in the categories Ozone layer depletion potential (OLDP), photo-oxidant creation potential (POCP), marine aquatic ecotoxicity potential (MAETP), human toxicity potential (HTP), ecotoxicity—air (ET-A), and human health /non-cancer –ground/surface soil (HHNC-GS). The manufacturing stage has two main contributors to impact scores, electricity production for the manufacturing process, and heavy truck transportation for distribution of filled beverage bottles from manufacturing to retail. In GWP, AP, POCP, and MAETP, electricity production accounts for about 60 percent of impact scores and truck transportation for 30 percent, with other fuels making up the balance.

In several toxicity categories electricity production is more dominant. About 75 percent of ET-A, 80 percent of TETP, and over 90 percent of HHC-A and HHNC-A scores is due to heavy metal emissions during electricity production, including mercury, chromium, nickel and arsenic. Electricity production also accounts for more than 90 percent of the smog impact score in the form of isoprene emissions

Human health (HH)-Criteria pollutants, mostly NOx and SOx, are split about evenly between electricity production and truck transportation. In HTP and EP-A, about 60 percent is due to truck transportation and 30 percent to electricity production. Barium is again implicated, being significant in the production of diesel fuel.

In TRACI ground-surface soil toxicity categories the production of lubricating oil for use in plastic molding machinery is the main driver. Arsenic, lead, and chromium emissions to soil are the culprits.

6.2.4 Use and Disposal

Impacts from the use and disposal stage are dominated by the polyethylene terephthalate (PET) landfilling process adapted from Ecoinvent. This process accounts for 96 percent to 99 percent of impact scores in all categories in which the use and disposal phase has a significant contribution. The primary environmental impact of landfilling is eutrophication due to the chemical oxygen demand of materials that enter groundwater. Toxicity impacts are again dominated by heavy metals released into soil and water. The eutrophication potential (CML) toxicity impacts in all categories are mostly attributable to vanadium emissions to fresh water. Vanadium is used in Swiss waste management facilities as a catalyst for cleaning incineration exhaust. Incineration is used in the Ecoinvent database to process residual sludge that is obtained through treatment of landfill leachate, which accounts for its presence in the landfill inventory. This flow is probably not applicable to U.S. conditions. TRACI toxicity impacts are dominated by other heavy metals including copper, zinc, arsenic, lead, and cadmium.

6.2.5 Materials Recovery

Materials recovery had a generally small contribution to nearly all impact categories. Because materials recovery consists of a wide variety of distinct processes, its impact profile is quite complex.

Around 40 percent of greenhouse gas emissions during the materials recovery stage are accounted for by gasoline consumption for consumer travel to recycling drop-off facilities. This figure is highly dependent on the choice of allocation for this process. We elected to allocate 25 percent of a 1.6-km round trip to recycling drop-off; however, some studies assume that drop-off of CRV containers is burden-free (Franklin Associates, 2010). After personal transportation, the remainder of GWP comes from a variety of transportation modes and fuel production processes.

A number of impact categories eutrophication potential (EP), eutrophication potential—water (EP-W), freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), exotoxicity—water (ET-W), human health/cancer—water (HHC-W), and human health/non-cancer—water (HHNC-W) receive 70-99 percent of their scores from the landfilling of polypropylene waste from caps and labels discarded during material recovery. These impacts are largely reflected by the landfilling impacts discussed in section 4.2.4 above.

Energy production and consumption accounts for the materials recovery stage's acidification potential (AP), photo-oxidant creation potential (POCP), eutrophication potential—air (EP-A), and smog scores, split among electricity generation for operating facilities, fuel production and transport.

The most surprising impacts, accounting for over half the impact scores in the categories of terrestric exotoxicity potential (TETP), exotoxicity—air (ET-A), exotoxicity—ground/surface soil (ET-GS), human health cancer—air (HHC-A), human health cancer—ground/surface soil (HHC-GS), human health/non-cancer—air (HHNC-A), and human health/non-cancer—ground/surface soil (HHNC-GS), come from the production of zinc-galvanized steel baling wire, used to package baled post-consumer polyethylene terephthalate (PET) for shipment to reclaimers. A variety of toxins are released to soil and air from both the steel production and zinc plating processes, including chromium, mercury, arsenic, lead, zinc, copper, and dioxins.

6.2.6 Reclamation

Reclamation has substantial impacts in a number of toxicity categories, exceeding 50 percent of total life cycle impacts in ET-GS, HHC-W, and HHNC-W, and exceeding 25 percent of total life cycle impacts in ET-W, HHC-GS, and HHNC-GS. The ground-surface soil impacts stem from the production process for sodium hydroxide (NaOH). The NaOH production process includes emissions of lead, chromium, barium, arsenic, copper, and zinc to soil. The water-borne toxicity impacts originate in disposal of residual waste to landfill, which includes emissions of lead, cadmium, copper, and zinc to fresh water. Landfilling also contributes the majority of the stage‘s eutrophication scores. A third of the eutrophication scores for the reclamation stage are due to waterborne emissions from the reclamation process itself. Disposal of residual waste to landfill contributes to FAETP in the form of copper, vanadium, and other heavy metal emissions (see landfill discussion in section 4.2.4)

Environmental impacts (excluding toxicity) stem from the usual sources. The reclamation process itself has significant eutrophication impacts due to the disposal of wastewater from washing post-consumer polyethylene terephthalate (PET). Electricity generation, natural gas combustion and ocean transport account for the reclamation stage's impacts in global warming potential (GWP), acidification potential (AP), criteria pollutants and smog. The toxicity categories of human toxicity potential (HTP), marine aquatic exotoxicity potential (MAETP), and terrestric exotoxicity potential (TETP) are well distributed among the different processes in this stage.

7 Interpretation

7.1 Sensitivity Analysis of Key Parameters

The modeling choices and parameter values with the greatest significance on the outcome are discussed here. We investigate the sensitivity of four stages of the product life cycle:

- Cradle-to-polymer
- Beverage manufacture
- Materials recovery
- Reclamation

The use phase was not evaluated in the sensitivity analysis because impacts from this phase are almost entirely related to the landfilling of non-recycled polyethylene terephthalate (PET). Use phase indicators are thus directly proportional to the amount of PET landfilled, and can be expected to decrease proportionately with an increase in the recycling collection rate.

The percentage changes reported in Tables 5.1, 5.2, and 5.4 are differences between the U.S. LCI case and the comparison case. They are computed as **(comparison - model) / model**, where **model** represents the U.S. LCI model used in the 2009 Baseline scenario, and **comparison** represents the comparison case. Thus, a large positive number indicates the comparison case has much higher impacts, while a number approaching -100 percent indicates that the comparison case registers few or no impacts. These values represent percentage differences over the *entire life cycle*.

7.1.1 Cradle-to-polymer

We did not parameterize the cradle-to-polymer life cycle stage. Our impact results in this area are a direct reflection of the contents of the U.S. LCI database, with a few minor enhancements to fill existing data gaps. In order to estimate the adequacy of this data set, we compared cradle-to-polymer impact assessment results of our model with those of two existing PET resin inventory models based on the PlasticsEurope data set. Comparison I represents the European Reference Life Cycle Data system (ELCD) model of the PlasticsEurope data set, reference year 2005. Comparison II represents the Ecoinvent implementation of the PlasticsEurope data set of the same year. The results of the comparison are shown in Table 5.1. A value near 0 percent indicates that the two scores are very similar; a negative value indicates that the comparison has a lower score; a positive value indicates that the comparison has a higher score.

The results of the comparison show that the models are in agreement on primary energy demand, and in approximate agreement on global warming potential (GWP), smog and human health (HH)-Criteria. On many other categories there is considerable discrepancy. The baseline model registers higher impacts on most environmental categories (excluding global warming potential). The ELCD impacts are vastly lower in most, but not all, toxicity categories, showing a greater than 90 percent reduction in 9 out of 13 toxicity categories, and essentially a 100 percent

Table 5.1 Comparison of cradle-to-gate inventory models.
In this chart, a positive figure indicates that the impact score from the comparison is higher than the Baseline 2009 case. A negative amount approaching -100% indicates the comparison case registered little or no impact.

	Comparison I ELCD / APME	Comparison II Ecoinvent		Comparison I ELCD / APME	Comparison II Ecoinvent
PE-gross	7.5%	10.6%	FAETP	-99.5%	-97.1%
PE-net	7.3%	10.8%	MAETP	-93.5%	-82.3%
PE Renewable	31.4%	110.8%	TETP	629.2%	2141%
			HTP	-91.3%	-61.4%
GWP	36.7%	15.5%			
AP	-40.0%	-59.2%	ET-A	543.7%	1706%
EP	-10.3%	194.5%	ET-GS	-100.0%	67527%
EP-T	-29.8%	788.8%	ET-W	-99.7%	293.2%
OLDP	-100.0%	8765%	HHC-A	-70.9%	536.5%
POCP	-50.2%	-67.2%	HHC-GS	-100.0%	100659%
Smog	7.2%	-23.7%	HHC-W	-100.0%	-69.9%
HH-Criteria	-14.6%	-30.8%	HHNC-A	44.9%	1460%
			HHNC-GS	-100.0%	80773%
			HHNC-W	-100.0%	-76.6%

reduction in 5. The notable exceptions, terrestric ecotoxicity potential (TETP) and ecotoxicity—air (ET-A), result from substantially higher releases of chromium and nickel to air reported in the ELCD model.

In contrast, the Ecoinvent impacts are modestly to substantially lower in many environmental impact categories, but substantially higher in many toxicity categories. The scores range from a greater than 60 percent reduction (in 5 out of 13 toxicity categories) to an enormous increase, ranging from 3x to over 1000-fold in the other eight categories. The increases are again due to metals, especially arsenic, chromium, vanadium, lead, copper, and barium. In many cases the metals are present in similar proportions, but in much greater magnitudes in the Ecoinvent model. These discrepancies are likely due to the substantial difference in methodology, particularly regarding system boundaries, between the Ecoinvent and the U.S. LCI databases. However, inclusion of a broader range of processes such as capital equipment manufacture and infrastructure are unlikely to account for the vast difference between the results.

The positive results of the comparison are that our model's use of primary energy and the associated impacts are well modeled, suggesting that the U.S. LCI dataset may be suitable for life cycle environmental assessments that do not involve toxicity. On the other hand, the dramatic dissimilarity of toxicity impacts among different inventory models suggest that inventory data pertaining to emissions of toxic substances is inconsistent, and toxicity impact indicators should be regarded cautiously (see section 5.2.2).

7.1.2 Beverage Manufacture

Beverage manufacture is dominated by two parameter values: the electrical energy required per kg of injection stretch blow molding (default: 6.5 MJ per kg polyethylene terephthalate, or PET); and the transport distance of pre-consumer filled bottles to retail (default: 72 km). We compared the life cycle impacts in the base model to the impacts that result if each of these parameters were increased by 50 percent. Because the life cycle model is linear, the resulting increases in impact scores are equal to the decreases that would result from the parameters being reduced by 50 percent. The results are shown in Table 5.2.

Table 5.2 Sensitivity analysis, Injection Stretch Blow Molding and Beverage Distribution

	Stretch Blow Molding +50% Elec.	Distribution +50% tkm		Stretch Blow Molding +50% Elec.	Distribution +50% tkm
PE-gross	7.9%	1.5%	FAETP	1.5%	3.1%
PE-net	8.1%	1.5%	MAETP	8.3%	2.1%
PE Renewable	29.4%	0.1%	TETP	10.6%	0.3%
0			HTP	3.1%	2.6%
GWP	10.3%	2.5%			
AP	9.9%	1.5%	ET-A	6.3%	0.7%
EP	1.7%	1.6%	ET-GS	1.0%	0.1%
EP-T	0.8%	0.7%	ET-W	1.2%	1.6%
OLDP	1.4%	0.1%	HHC-A	16.2%	0.3%
POCP	7.0%	1.5%	HHC-GS	1.2%	0.1%
Smog	8.0%	5.5%	HHC-W	0.4%	0.9%
HH-Criteria	8.8%	3.2%	HHNC-A	12.2%	0.3%
			HHNC-GS	1.1%	0.1%
			HHNC-W	0.3%	0.9%

The results demonstrate that the electrical power required for injection stretch blow molding is a highly significant parameter in the model, with a 50 percent change in the parameter resulting in large increases in a number of impact categories, including an 8 percent increase in primary energy demand, a 10 percent increase in global warming potential, and a 20 percent increase in smog creation potential. These impacts reflect the composition of the Western Electricity Coordinating Council production mix, which was assumed to provide electricity to operations occurring in California.

In contrast, increasing the freight transportation of filled beverages by 50 percent had a comparatively more modest impact on total life cycle emissions. Air emissions associated with truck transportation lead to increases in global warming potential (GWP), eutrophication potential—air (EP-A), and Criteria pollutants 2.5-6 percent , and other impact categories are affected to a lesser extent. However, it is notable that some beverages are transported much longer distances than 72 km. Under the current model, beverage distribution requires approximately 0.046 MJ per km distribution, which implies that a beverage distribution distance of 1,040 km by truck would require as much delivered energy as the entire product system (47.8 MJ). Beverages delivered by ship would have to travel about 8,500 km to incur the same energy cost.

7.1.3 Materials Recovery

To understand different aspects of the materials recovery model, we performed a parametric

Table 5.3 Scenario Analysis of Materials Recovery - 1 kg of PET recycled
Numbers in red denote higher indicators than the base case; numbers in green denote lower indicators.

	Baseline	Curbside	Dropoff	Dropoff No Alloc.	Local	Remote
Curbside Share	**24%**	**100%**	**0%**	**0%**	**-**	**-**
Local Share	**69%**	**-**	**-**	**-**	**100%**	**0%**
Buyback Allocation	**0.25**	**-**	**-**	**0**	**-**	**-**
Net Primary Energy, MJ	2.56	1.87	2.78	1.14	2.39	2.97
Net Delivered Energy, MJ	1.89	1.43	2.04	0.57	1.74	2.24
Net Energy of Transport, MJ	1.64	1.17	1.78	0.31	1.48	1.98
Total Freight, kg·km	199	188	203	173	85	458
Heavy Truck Transport, kg·km	123	123	123	123	0.	401
GWP, kg CO_2-eq	0.201	0.149	0.217	0.091	0.188	0.231
AP, g SO2-eq	1.08	1.49	0.95	0.73	0.98	1.30
EP, g PO4-eq	1.97	2.08	1.93	1.92	1.95	2.00
POCP, g C2H4-eq	0.134	0.115	0.140	0.069	0.123	0.160
HH-Criteria, g PM2.5-eq	0.430	0.692	0.348	0.265	0.378	0.549

scenario analysis of the materials recovery stage in which we allowed several parameters to vary and observed their effects on the stage's output. Because materials recovery had a generally small contribution to the total life cycle, we do not compare the results to the total life cycle impacts. Instead, we compare selected impacts of several alternative scenarios to the base case looking at this stage only. *For this section only*, the functional unit is 1 kg of polyethylene terephthalate (PET) bottles transported from disposal to processing.

The table below presents the **Baseline** scenario and five alternate scenarios:

- **Curbside** (100 percent of bottles are collected through curbside collection);
- **Dropoff** (100 percent of bottles are dropped off by consumers at recycling centers);
- **Dropoff / No Alloc.** (100 percent of bottles are dropped off by consumers, but 0 percent of the trip is allocated to recycling);
- **Local** (all PET is processed in the county in which it was collected); and
- **Remote** (all PET is processed at a centralized location distant from the point of collection).

The comparison between the **Dropoff** and **Dropoff / No Alloc.** scenarios indicates the amount of impact attributed to a consumer returning bottles to a recycling center at 25 percent allocation. Specifically, these scenarios differ by 1.64 MJ of primary energy and 1.47 MJ of transportation energy. This is the energy demand associated with the consumption of 42 mL of gasoline (0.011 gal) for personal transport to the dropoff location. The global warming potential from this fuel is about 0.126 kg CO_2-eq. The comparison demonstrates that the allocation of personal transport to the recycling center is among the most significant parameters in determining impacts of this phase. Under these assumptions, if a customer made a journey of 13 km whose sole purpose was to deliver 1 kg of PET bottles to recycling (100 percent allocation), then that journey would require as much delivered energy as the entire product system (47.8 MJ).

The difference between the **Curbside** and **Dropoff / No Alloc.** scenarios demonstrates the impacts of curbside commingled recycling for beverage bottle recovery. Curbside recycling requires a modest amount more energy, (0.73 MJ) which is used primarily in the operation of trucks collecting recycled materials.

Comparison of the **Local** and **Remote** scenarios demonstrates the impact of long-distance trucking of post-consumer polyethylene terephthalate (PET) to distant processing facilities. The remote scenario has the highest impacts in every category, but the difference between the remote scenario and the baseline is generally small (around 15-28 percent).

7.1.4 Reclamation

There is only one source of inventory data on PET reclamation, so it is difficult to assess the accuracy of the impacts from the reclamation gate-to-gate process itself. Instead, we looked at the effects of two changes to the secondary material system: a 50 percent increase in the amount of sodium hydroxide (NaOH) required for reclamation, and an increase of the PET bottle collection rate from 73 percent to 80.3 percent (an increase of 10 percent)

Table 5.4 Sensitivity analysis, reduced NaOH demand, and increased collection.

	NaOH +50%	Collection Rate +10%		NaOH +50%	Collection Rate +10%
Secondary Material	0.0%	10.7%	FAETP	0.0%	0.5%
			MAETP	0.1%	0.7%
PE-gross	0.2%	0.7%	TETP	9.8%	2.9%
PE-net	0.3%	0.7%	HTP	0.1%	0.6%
PE Renewable	0.4%	1.1%			
			ET-A	3.5%	2.4%
GWP	0.3%	0.9%	ET-GS	31.9%	4.4%
AP	0.1%	0.9%	ET-W	1.6%	1.5%
EP	0.1%	-5.7%	HHC-A	1.7%	1.1%
EP-T	0.1%	-6.6%	HHC-GS	19.7%	2.0%
OLDP	13.1%	0.7%	HHC-W	0.0%	6.6%
POCP	0.1%	0.6%	HHNC-A	3.5%	2.0%
Smog	0.1%	1.5%	HHNC-GS	25.9%	3.3%
HH-Criteria	0.2%	1.1%	HHNC-W	0.0%	6.9%

Increasing NaOH requirements leads to dramatic life-cycle increases in the impact scores for several toxicity categories, as well as ozone layer depletion. These results directly reflect the emissions included in the Ecoinvent sodium hydroxide (NaOH) process inventory. Due to inconsistencies in toxicity results, we urge caution in interpreting these figures (see section 5.2.2).

Increasing the collection rate leads to increases in the activity levels of the materials recovery and reclamation stages, and decreases in landfilling requirements. The former are visible in the increased toxicity impact scores, while the latter is evident in reduced eutrophication potential. This case also results in an increased amount of secondary PET co-product. If used in a manner which displaces primary material, this may register additional benefits (see section 5.2.3).

With respect to energy consumption, neither scenario leads to significant increases in energy use, global warming potential, or other energy-related indicators.

7.2 Life Cycle Interpretation

We modeled the life cycle of single-use polyethylene terephthalate (PET) bottles used to deliver beverages to California consumers. The majority of energy use and related environmental impacts occurred before the use phase, but significant toxicity impacts were generated from post-consumer handling, including both disposal to landfill and recycling. However, irregularities in toxicity impact assessment results suggest that toxicity data in the U.S. LCI database is less complete than in the Ecoinvent database, and studies using U.S. LCI data to assess toxicity should be regarded cautiously.

7.2.1 Environmental Impacts

Most environmental indicators regarding air pollution and air quality, including global warming potential (GWP), acidification potential (AP), photo-oxidant creation potential (POCP), smog, and human health (HH)-Criteria, directly reflect the effects of combusting fossil fuels to produce energy. Therefore, the contribution of each stage to these impact scores is largely proportional to that stage's relative demand for delivered energy. The capacity for improvement in these impact areas is thus dependent on the ability to reduce energy demand.

The data demonstrate that the most energy-intensive life cycle phase varied depending on the inventory metric. Raw material extraction demanded the most primary energy resources; however, these resources became feedstocks and were not combusted as energy. Beverage manufacture required more primary energy than polymer production, but both stages delivered about the same useful energy to transformation processes. In other words, more primary energy was lost as waste heat in operating the manufacturing phase than in the polymer production phase. This reflects the strong dependence of manufacturing on electrical power, which is less energy-efficient than combustion processes. Polymer production did result in additional impacts, beyond those associated with energy production, in several categories because of the release of volatile organic compounds and particulates to the air. The AP, POCP, and HH-Criteria impact scores could all be reduced through improved pollution controls during the polymer production stage.

Eutrophication impacts are more pronounced in post-consumer processes. Landfill processes invoked for the disposal of non-recycled PET and polypropylene (PP) waste, as well as reclamation yield losses, all contribute to eutrophication scores. The reclamation process also results in substantial emissions of organic materials to wastewater, contributing about 10 percent of total life cycle eutrophication impacts.

Transportation made up approximately 1/3 of delivered energy and 12 percent of total primary energy demand, driven primarily by the manufacturing stage. Transport of polymer resins to the bottling facility is the most costly transportation step, followed by beverage distribution. Together, they make up only 1/3 of freight requirements but more than 2/3 of transportation energy. The distance filled beverages are transported is an important parameter in the model. We assumed beverages were transported an average of 72 km, which is the distance reported in the U.S. Census Commodity Flow Survey (see section 2.3.1); however, certain beverage products are typically transported a much greater distance (Gleick and Cooley, 2009). Beverage distribution distances approaching the hundreds or thousands of miles would quickly overwhelm other life cycle impacts. A beverage product distribution distance of 1,000 km by truck or 8,500 km by ship would require an amount of energy equal to the entire product system's delivered energy requirements (see Section 5.1.2).

The California scenario results demonstrate that locating reclamation capacity within California and increasing the recycled content of bottles can lead to reduced freight transport and transportation energy. However, these gains are modest. There is a greater potential for improvements through improved utilization of secondary material in ways that displace primary production (see Section 5.2.3). This goal may be advanced by promoting polyethylene terephthalate (PET) reclamation within California.

Materials recovery did not contribute significantly to the energy demand for the life cycle, suggesting that the overall PET bottle life cycle impacts cannot be significantly improved through changes to the recycling collection process. Instead, it may be beneficial to provide incentives to further increase PET collection and recycling, because it has comparatively low impacts and potentially significant benefits.

7.2.2 Toxicity Impacts

Toxicity findings are inconclusive. Any impact assessment result is contingent on there being correspondence between the inventory information used (type and amount of emissions) and the impact characterization models used (magnitude of environmental effects due to each emission). Upon close inspection of the toxicity results produced by our model, we conclude that the indicator scores may not be reliable estimates of potential toxic effects because of possible data gaps in both inventory and impact assessment modeling. The toxicity indicators reported here should be taken as preliminary estimates only.

Close inspection of toxicity impact category scores, combined with sensitivity analysis of our inventory data, led us to conclude that toxicity impact scores included in this report are an unreliable basis for comparison of life cycle stages or different scenarios. There are three primary reasons for this conclusion:

1. When applying the same impact assessment methodology to three different PET polymer cradle-to-gate inventory data sets, the results differ over several orders of magnitude. This suggests that inventory data are reported with widely varying completeness criteria. In particular, processes in the Ecoinvent database are likely to have far higher toxicity impact scores than processes from the U.S. LCI database according to the TRACI methodology, and may have much lower impact scores according to the CML methodology.
2. Heavy metals vastly dominate organics in all toxicity categories, even though petroleum refining and polymer production involves organic substances known to be toxic. The elementary interpretation of this observation is that organic substances associated with plastic production do not present a toxic threat in comparison to heavy metals. However,

the following interpretations are also possible:

- That organic substances are poorly represented in process inventories;
- That data gaps exist which conceal the impacts of organics; or
- That methodological decisions in impact characterization cause results to amplify the impacts of heavy metals relative to organics.

It is beyond the scope of this report to evaluate these possibilities in detail.

3. Many indicator scores are dominated by one or a few flows. This suggests that the omission or erroneous reporting of one or a few significant flows could dramatically alter the results, adding to concerns about the thoroughness of inventory data.

The indicators show mixed results, with different methodologies implicating different life cycle stages. Inconsistencies in system boundary definitions or modeling methodology between the U.S. LCI and Ecoinvent process inventory data sets probably led to inaccuracies in these indicator results. The TRACI indicators largely implicate post-consumer stages, especially reclamation, as having the greatest contributions to toxicity. However, these stages also have the greatest dependence on Ecoinvent data, in the form of sodium hydroxide and landfill process inventories. The results reported in Section 5.1.1 demonstrate that Ecoinvent data tend to have much higher toxicity scores.

The results from the two methodologies do not corroborate one another. For instance, both methodologies register significant aqueous toxicity from fossil fuel extraction, but for different reasons (barium in CML, lead in TRACI), each of which manifests in one database but not the other. Most toxicity indicator scores are dominated by one or two flows in any given life cycle stage. These flows are almost always heavy metals and metalloids like lead, arsenic, barium, copper, chromium, cadmium, nickel, and zinc. The insignificance of organic chemicals in indicator results raises concerns that data gaps exist in either inventory or characterization of toxic flows. Without detailed investigation of the impact characterization models used it is impossible to say whether organic chemicals are in fact insignificant compared to metals, or whether their impacts are uncharacterized or inaccurately characterized.

In summary, toxicity may not be well characterized by the life cycle impact assessment models used, and case-by-case evaluations of specific emission scenarios should be performed.

7.2.3 Open-Loop Recycling

Secondary polyethylene terephthalate (PET) that is closed-loop recycled reduces environmental impacts of the product system by reducing the consumption of primary material. However, in the case of open-loop recycling, environmental benefits would also be realized if the secondary material were used in place of primary material in a manufacturing application. We report an estimate of the environmental impacts that would be avoided.

Credits are sometimes awarded to product systems in life cycle assessments in order to account for the benefits of producing recycled material, through a process called “system expansion.”

While we did not include those credits in our model, we do report the impacts of producing an amount of primary polyethylene terephthalate (PET) equal to the amount of secondary PET, which is a co-product of our system (Table C.8 in Appendix C below). In a life cycle model that used system expansion, the impacts below could be subtracted from the life cycle impacts to reflect the benefits of using recycled material. In the base case, avoided production of 0.55 kg of primary PET would reduce primary energy demand by 36.5 MJ (30.5 percent of total) and reduce greenhouse gas emissions by 1.38 kg CO_2-eq (23.8 percent of total). Under the California scenario, this secondary PET would be obtained from a California reclaimer.

If secondary PET is used in a product system where it does not displace any other material (i.e. in a product system which would not be produced if secondary PET were not available), or where it displaces a material other than PET, then an allocation problem is created. The impacts reported in this study would need to be allocated between the primary product system (beverage delivery) and the secondary product system (secondary PET). In that case, some fraction of the impacts reported here would register as the burdens of the secondary PET used in the other product system, which could then treat the PET as any other primary material. The remainder of impacts (not allocated to the secondary PET) would register as the impacts of the beverage system.

8 Conclusion

We have modeled the life cycle environmental impacts of the delivery of beverages to California consumers in disposable polyethylene terephthalate (PET) bottles. **Our reference flow** was the use of 1 kg of PET resin, made up of 0.961 kg primary PET and 0.039 kg secondary PET, to contain 27.9 L of California-average beverage, plus 0.143 kg of polypropylene (PP) to make bottle caps and labels. Delivery of this product system generates 119.6 MJ net primary energy demand, requires 20,500 kg·km of freight services, produces 0.727 kg of solid waste and 0.55 kg of secondary PET that is open-loop recycled.

On a **volume of beverage basis**, delivery of one liter of California-average beverage has a primary energy demand of 4.29 MJ (net), requires 737 kg·km of freight services, and produces 20 g of secondary PET and 26 g of waste. One liter of bottled water has a primary energy demand of 3.22 MJ (net), requires 565 kg·km of freight services, and produces 14 g of secondary PET and 19 g of waste. One liter of carbonated soft drink has a primary energy demand of 4.80 MJ (net), requires 825 kg·km of freight services, and produces 23 g of secondary PET and 29 g of waste. These results are summarized in Figure S-3 and in Table 3.1.

Several **environmental indicators** regarding air pollution and air quality, including global warming potential (GWP), acidification potential (AP), photo-oxidant creation potential (POCP), smog, and human health (HH)-Criteria, directly reflect the effects of combusting fossil fuels to produce energy. Therefore, the contribution of each stage to these impact scores is largely proportional to that stage's relative demand for delivered energy. Both polymer production and beverage manufacture are significant energy users and together contribute more than 80 percent of these impact scores. In contrast, eutrophication impacts are more pronounced in post-consumer processes, especially landfill disposal of non-recycled PET and PP waste and reclamation yield losses.

Transportation made up approximately 1/3 of delivered energy and 12 percent of total primary energy demand, driven primarily by the manufacturing stage. Transport of polymer resins to the bottling facility is the most costly transportation step, followed by beverage distribution. Together, they make up only 1/3 of freight requirements but more than 2/3 of transportation energy requirements. A beverage product distribution distance of 1,000 km by truck or 8,500 km by ship would double the amount of delivered energy required by the product system.

Toxicity indicators show mixed and unreliable results, with different methodologies implicating different life cycle stages. Inconsistencies in system boundary definitions or modeling methodology between the U.S. LCI and Ecoinvent process inventory data sets probably led to inaccuracies in these indicator results. Most toxicity indicator scores are dominated by one or two flows in any given life cycle stage. These flows are almost always heavy metals and metalloids like lead, arsenic, barium, copper, chromium, cadmium, nickel, and zinc. The insignificance of organic chemicals in indicator results raises concerns that data gaps exist in either inventory or characterization of toxic flows.

The **material recovery** stage has minimal environmental impacts. We find that California's system for collecting post-consumer beverage containers requires approximately 2.6 MJ of primary energy per kg of polyethylene terephthalate (PET) recovered. The largest share of this amount is attributable to consumers traveling by vehicle to drop off containers at recycling centers. If materials recovery were performed entirely through curbside recycling collection, primary energy demand would measure 1.9 MJ per kg PET recovered.

The product system produces **secondary PET** as a co-product which can be used in place of primary polymer in another product system. If this material is put to beneficial use, its environmental burdens would have to be determined through allocation. The base case scenario led to production of 0.55 kg of secondary PET. If used to directly replace an equal amount of primary PET, the recycled material would reduce primary energy demand by 36.5 MJ (30.5 percent of total) and reduce greenhouse gas emissions by 1.38 kg CO_2-eq (23.8 percent of total).

The alternative **California Scenario** represents an increase in the recycled content (to 15 percent) of bottles and the localization of secondary PET reclamation within the state of California. This scenario results in significant reductions in post-consumer freight requirements and somewhat more modest reductions in energy requirements and atmospheric emissions. Potential improvements in life cycle impacts are limited by the fact that polymer production and beverage manufacturing do not change under the California scenario. There is a greater potential for improvements through improved utilization of secondary material in ways that displace primary production.

Appendix A - Geographical Analysis of Post-consumer PET Reverse Logistics

The state of California has established a two-step process for recycling of deposit beverage containers, consisting of collection and processing. The collection stage is the point at which the consumer returns the bottle and recovers the deposit amount; at the processing stage the bottle is "cancelled," typically by being crushed into a bale. California's recycling system defines "convenience zones" 0.5 miles in radius around every supermarket[11]. If a given convenience zone does not have a recycling center and also is not served by a curbside collection program, the supermarket is obligated to accept deposit containers from consumers and to pay out deposits. Of California's 58 counties, 56 had active collection facilities in 2007, the exceptions being Alpine County and Sierra County. Those two counties have a combined population of fewer than 5,000 inhabitants. In 2007 statewide there were 2,105 active recycling centers, up from 976 in 2001; 159 processors compared with 85 in 2001; and 550 curbside programs in operation compared with 404 in 2001.[12]

California's system allows the market to determine where best to locate processing facilities. In 2009, 33 counties had at least one active processor. Over 33 percent of bottles were processed in Los Angeles County, and a further 16 percent were processed in Riverside County. These figures reflect a trend of centralization in processing.

We performed an analysis of the geographic distribution and activity level of collection and processing facilities based on a combination of publicly available data and internal statistics provided by the Department of Conservation in 2008 and 2010. Cal Recycle (which includes the Division of Recycling that was formerly part of the Department of Conservation) provided us with data reporting the weight of polyethylene terephthalate (PET) collected in each county and the weight of PET processed in each county for each year from 2001 to 2009. This enabled us to estimate the amount of PET that was recycled within the same county it was collected, and to make projections about the average distance the PET was transported between collection and processing.

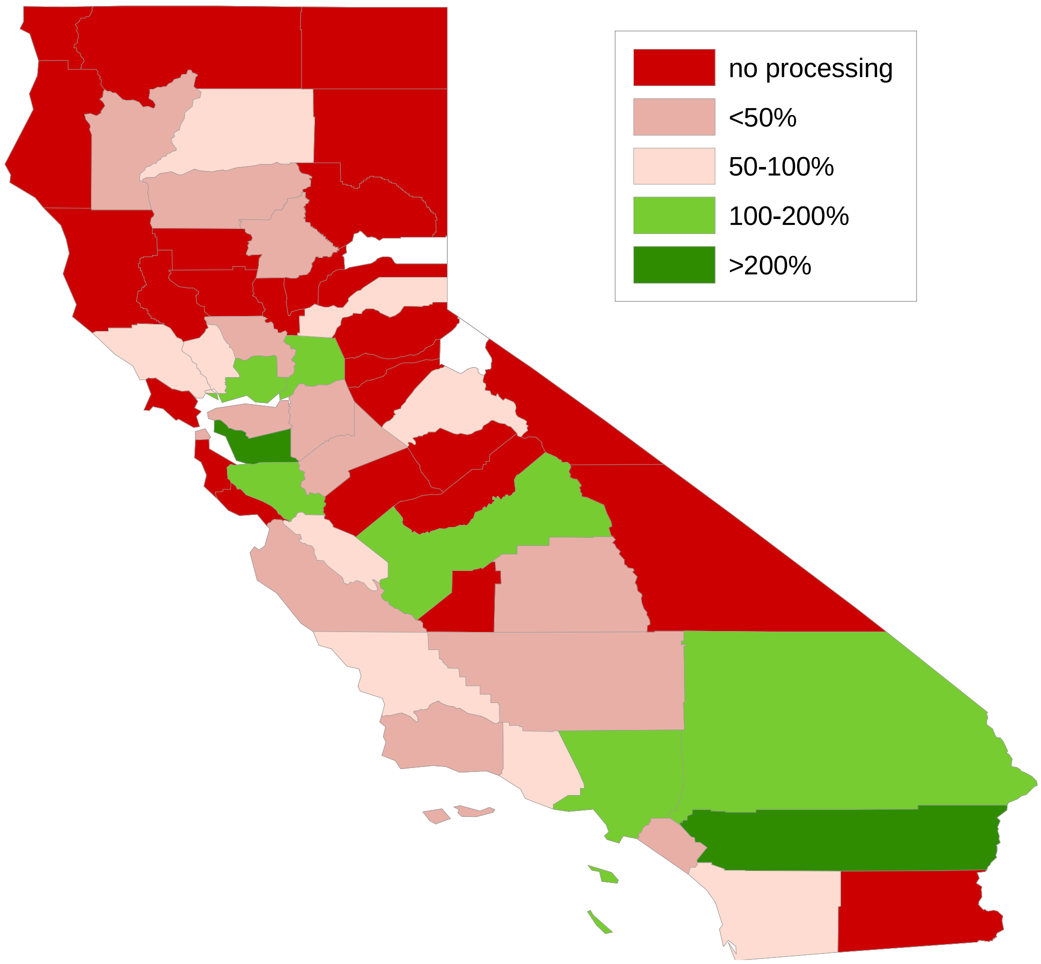
For each county we collected the following information:

- **C**, Collection activity, reported in mass of PET;
- **N**, Number of processing facilities;

[11] "Supermarket" means a full-line, self-service retail store with gross annual sales of two million dollars ($2,000,000), or more, and which sells a line of dry grocery, canned goods, or nonfood items and some perishable items. (California Public Resources Code, section 14526.5). Supermarkets can also be exempted from the requirement.

[12] Facility counts were determined from a set of spreadsheet documents made available to the public via the CalRecycle FTP site, ftp://publicftp.calrecycle.ca.gov/BevContainer/Data/ . The number of active facilities for a given year was computed by counting all facilities with "Operational date" before January 31 of the year in question and with "Decertification date" either empty or after December 1 of that year. The counts reported here are based on documents accessed November 3, 2008.

Processing as Percent of Collection – 2007



- **P**, Processing activity, reported in mass of polyethylene terephthalate (PET);
- **A**, county land area.

In all cases, a fraction of bottles collected in a county were assumed to be processed in the county in which they were recovered, and the remaining bottles were processed in a remote county. We refer to these amounts as the "local fraction" and the "remote fraction." The key parameter is **P/C**, the ratio of processing to collection activity in a given county. A county's local fraction is equal to this ratio if the ratio is less than 1, and is equal to 1 if this ratio is greater than 1. A county's remote fraction is equal to 1 minus its local fraction. Counties in which processing exceeds collection are called "surplus counties" because they have a surplus of processing capacity. These counties are assumed to handle the remote fractions of the other counties.

For each county we computed the local and remote fractions of PET collected. For each county with a nonzero local fraction (i.e. for each county with processing facilities) we computed a statistical average distance to the in-county facility based on the land area of the county. This local distance is equal to $\sqrt{\ /\ }$. Because this distance does not include knowledge of actual roadways, topography, or population distribution, it has a high level of uncertainty.

Local distances ranged from 10.9 km (Alameda County, with 18 processors) to 91 km (Trinity County, with one processor). For each county with a remote fraction, the remote distance is calculated as a weighted average of the distance from this county's centroid to the centroids of each surplus county. The weighting is performed on the basis of the surplus processing capacity of each surplus county and not based on proximity to the originating county. For this reason, the remote distance is likely overestimated by our model. Remote distances ranged from 237 km (Orange County) to 892 km (Del Norte County). We then computed the total short-haul and long-haul freight for each county as follows:

short-haul freight = collection × local fraction × local distance

long-haul freight = collection × remote fraction × remote distance

We computed the average short-haul distance as the sum of short-haul freights across counties, divided by the total mass of polyethylene terephthalate (PET) shipped locally. This amount comes out to 30.4 km for 2007. Similarly, the average long-haul distance is computed as the sum of long-haul freights divided by the total mass of PET shipped remotely. This distance comes out to 348 km for 2007. Finally, we computed the fraction of total freight which is represented by long-haul freight; for 2007, this fraction was 30.7 percent.

The design of our logistics model is not optimal (i.e. bottles may travel a shorter distance than the model indicates) and its results are not verifiable. Certain assumptions made in constructing the model are not representative of real-world conditions. For instance, curbside commingled recycling is less likely to be transported a great distance than source-separated recycling, but our model treats them both the same. The intention of the model was to develop a plausible description of post-consumer logistics that was consistent with available data, and to err on the side of overestimating transport distance.

Logistics Modeling

We used the above analysis to model bottle reverse logistics as two possible routes:

A. Consumer dropoff at buyback center (76 percent of bottles)

1. Transportation by the consumer from consumption to collection. The transportation distance was modeled as 1.6 km round trip in an average passenger car, with 25 percent of the trip being allocated to recycling dropoff.
2. The average local fraction of bottles (69.3 percent) are shipped the average short-haul distance (30.4 km) to a local processing facility.
3. The average remote fraction of bottles (30.7 percent) are shipped the average long-haul distance to a remote processing facility (348 km).

B. Collection via a curbside program (24 percent of bottles). Footnote: this figure includes commercial collection programs as well as residential curbside programs.

1. Curbside collection is modeled as a combination of freight services and collection services. Freight is only assigned to the average short-haul distance assumed traveled by the bottle (30.4 km to a local processing facility). 100 percent of curbside bottles are assumed to travel this short-haul distance. In addition, curbside collection services are modeled as requiring the combustion of diesel fuel to operate the collection vehicle. See section 2.3.3 for more information.
2. In addition to the short-haul distance, the average remote fraction of bottles (30.7 percent) are assumed to travel the average long-haul distance (348 km) in transit to an out-of-county processor.

According to our results, the average total distance traveled by a bottle between use and material recovery was 132 km:

$$\begin{aligned}\text{Avg. Distance} &= \text{buyback share} \times \text{buyback km} + \text{curbside share} \times \text{curbside km} \\ &= 0.76 \times (1.6\text{ km} + (0.693 \times 30.4\text{ km}) + (0.307 \times 348\text{ km})) \\ &\quad + 0.24 \times (30.4\text{ km} + (0.307 \times 348\text{ km})) \\ &= \mathbf{132\ km}\end{aligned}$$

We computed the sensitivity of this distance to changes in each of the following parameters. The table below indicates the new average distance estimate resulting from changes in each parameter. These results show that the distance is most sensitive to the local fraction parameter.

Table A.1 Sensitivity analysis of distance estimate

Parameter	Base value	Adjusted value	Adjusted distance
	Defaults		132 km
Buyback local distance	30.4 km	45.6 km (+50%)	140 km (+6.1%)
Buyback local fraction	69.3%	50%	178 km (+35%)
Buyback remote distance	348 km	522 km (+50%)	173 km (+31%)
Curbside local distance	30.4 km	45.6 km (+50%)	135 km (+2.3%)
Curbside local fraction	69.3%	50%	148 km (+12%)
Curbside remote distance	348 km	522 km (+50%)	145 km (+9.9%)
Buyback AND curbside local distance	30.4 km	45.6 km (+50%)	144 km (+9.1%)
Buyback AND curbside local fraction	69.3%	50%	195 km (+48%)
Buyback AND curbside remote distance	348 km	522 km (+50%)	185 km (+40%)

Appendix B - Emission Factors for Truck Transportation

An important aspect of the life cycle of beverage bottles is the impact of heavy truck transportation. There is no established reference data set for emission factors from truck transportation in the U.S. Instead, there are a number of emissions estimation tools produced by the California Air Resources Board (CARB), the U.S. EPA, and others. There is a truck transportation process included in the U.S. LCI database, but it is based on unpublished assumptions by researchers working at Franklin Associates, the consulting firm that generated much of the data for the U.S. LCI database. Life cycle assessment software packages include a number of process inventories for freight transport, but most represent European conditions. Because of the inadequacies of existing U.S. process inventories for freight transport, we elected to design our own process inventories based on the emissions data embedded in the CARB EMFAC model. This model has the benefits of being based on empirical measurements and representing California conditions.

We desired a process inventory which represented fuel use and tailpipe emissions per unit of freight services (mass × transport distance, for which we use the unit t·km—metric ton-kilometer. 1 t·km = 1000 kg·km = 0.684 short-ton·mile). We also wanted to account for transportation "backhaul," which is the movement of empty trucks after delivering a shipment (Cooper et al., 2008). The EMFAC model includes data on vehicle size and trip distance but not payload. EMFAC estimates total truck emissions, and not just emissions from trucks carrying payloads. Therefore, it was necessary to estimate average payload weights and the percentage of truck miles traveled with empty payloads in order to tie EMFAC data to freight transport.
We made use of a truck transportation survey published by the Federal Highway Administration (Alam and Rajamanickam, 2007, p. Table 1) to generate our estimates. Based on that report, we estimated the average payloads of light-heavy-duty trucks (10,001--14,000 lb GVWR) to be 1.37 MT, of medium-heavy-duty trucks (14,001--33,000 lb GVWR) to be 5.35 MT, and heavy-heavy-duty trucks (33,001--60,000 lb GVWR) to be 14.31 MT. We used another FHWA report (Alam et al., 2007, fig. 3.6 and Table 3.4) to estimate empty fraction, looking particularly at "bulk" and "other" freight categories. We estimated that 30 percent of truck miles were traveled empty.

We then combined those estimates with the outputs of aggregated emissions from EMFAC to estimate a process inventory. EMFAC can be used to report average daily vehicle miles traveled, fuel use, and emissions by vehicle class for a calendar year. We used the following formula to normalize a given emission data point to a metric ton-kilometer basis:

$$\text{emission\_per\_tkm} = \text{emission\_per\_day} \times (\text{unit conversion}) / \text{tkm\_per\_day}$$

where

$$\text{tkm\_per\_day} = \text{VMT/day} \times (\text{unit conversion}) \times \text{avg\_payload} \times (1 - \text{empty\_fraction})$$

As a consequence of EMFAC reporting aggregate values, the use of a larger empty-fraction estimate will result in an increase in apparent emissions per metric ton kilometer.

The resulting emission factors are shown below. We used emissions of light-heavy-duty trucks to approximate the volume-limited transport of bulk recyclables.

Table B.1 Emission factors for truck transportation based on EMFAC Year 2007 data.

Class	Fuel type	Share of class	Avg. Pay-load	CO_2	CO	NOx	CH_4	NM VOC	Other ROG	SOx	PM2.5-10	PM2.5	Fuel Use
			MT	g/tkm	g/tkm	g/tkm	g/tkm	g/tkm	g/tkm	g/tkm	g/tkm	g/tkm	kg/tkm
LHD	gasoline	51.1%	1.37	575.32	11.871	1.639	0.0690	0.8462	0.5895	0.00531	0.01062	0.01416	0.1929
LHD	diesel	48.9%	1.37	349.35	0.721	4.283	0.0074	0.1534	0.0000	0.00370	0.01294	0.04436	0.1096
MHD	gasoline	15.8%	5.35	127.62	10.552	1.107	0.0635	0.7913	0.3097	0.00138	0.00276	0.00414	0.0475
MHD	diesel	84.2%	5.35	250.85	0.362	1.843	0.0018	0.0373	0.0000	0.00245	0.00646	0.04547	0.0789
HHD	gasoline	2.9%	14.31	39.83	7.273	1.038	0.0290	0.4050	0.0585	0.00052	0.00155	0.00207	0.0170
HHD	diesel	97.1%	14.31	117.47	0.362	1.233	0.0043	0.0872	0.0000	0.00112	0.00685	0.04942	0.0369

Key:
- LHD = Light-heavy-duty (10,001-14,000 lbs GVWR)
- MHD = Medium-heavy-duty (14,001-33,000 lbs GVWR)
- HHD = Heavy-heavy-duty (33,001-60,000 lbs GVWR)
- GVWR = Gross Vehicle Weight Rating
- NM VOC = Non-methane volatile organic compounds
- Other ROG = Other reactive organic gases

All rows assume 30 percent empty fraction of total vehicle travel.

Appendix C - Impact Indicators by Life Cycle Stage

Table C.1 Impact assessment results for the complete life cycle.

		2009 Baseline	Alt. (CA)	BW Variant	CSD Variant
Products					
Beverage Delivered	L	27.9	27.9	1000.	1000.
Secondary PET	kg	0.547	0.436	14.51	22.50
Secondary Mixed Plastic Waste	kg	0.018	0.018	0.47	0.72
Aluminum Hydroxide	kg	0.0072	0.0072	0.19	0.29
GaBi Inventory Metrics					
Net primary energy from renewable materials	MJ	3.287E+00	3.236E+00	8.937E+01	1.320E+02
Gross primary energy from resources	MJ	1.406E+02	1.292E+02	3.786E+03	5.641E+03
Net primary energy from resources	MJ	1.310E+02	1.205E+02	3.529E+03	5.259E+03
Impact Indicators, in kg					
CML2001 - Nov. '09					
Acidification Potential	SO2-eq	5.754E-02	5.233E-02	1.554E+00	2.303E+00
Eutrophication Potential	P-eq	1.093E-02	1.037E-02	2.921E-01	4.359E-01
Freshwater Aquatic Ecotoxicity Potential	DCB-eq	1.418E+00	1.261E+00	3.831E+01	5.709E+01
Global Warming Potential (100 years)	CO_2-eq	5.782E+00	5.309E+00	1.567E+02	2.325E+02
Human Toxicity Potential	DCB-eq	4.720E+00	4.221E+00	1.272E+02	1.904E+02
Marine Aquatic Ecotoxicity Potential	DCB-eq	7.718E+03	7.041E+03	2.084E+05	3.109E+05
Ozone Layer Depletion Potential (steady state)	R11-eq	7.235E-09	7.040E-09	1.911E-07	2.952E-07
Photochem. Ozone Creation Potential	C2H4-eq	7.867E-03	7.105E-03	2.109E-01	3.186E-01
Terrestric Ecotoxicity Potential	DCB-eq	4.109E-03	3.915E-03	1.097E-01	1.673E-01
TRACI 2002					
Ecotoxcity Air	2,4-DCP-eq	1.661E-02	1.550E-02	4.425E-01	6.764E-01
Ecotoxcity Ground-Surface Soil	Benz.-eq	1.095E-04	1.090E-04	2.900E-03	4.466E-03
Ecotoxcity Water	2,4-DCP-eq	2.167E+00	2.040E+00	5.793E+01	8.736E+01
Eutrophication	N-eq	8.881E-03	8.652E-03	2.356E-01	3.553E-01
Human Health Cancer Air	Benz.-eq	2.047E-03	1.938E-03	5.491E-02	8.298E-02
Human Health Cancer Ground-Surface Soil	Benz.-eq	9.773E-07	9.741E-07	2.582E-05	3.994E-05
Human Health Cancer Water	Benz.-eq	2.836E-02	2.753E-02	7.553E-01	1.156E+00
Human Health Criteria Air-Point Source	PM2,5-eq	1.823E-02	1.608E-02	4.967E-01	7.298E-01
Human Health Non Cancer Air	Tolu.-eq	1.067E+00	1.010E+00	2.851E+01	4.335E+01
Human Health Non Cancer Ground-Surface Soil	Tolu.-eq	4.969E-03	4.951E-03	1.314E-01	2.029E-01
Human Health Non Cancer Water	Tolu.-eq	9.171E+02	8.919E+02	2.441E+04	3.738E+04
Smog Air	NOx-eq	2.477E-05	2.072E-05	6.837E-04	9.921E-04

Table C.2 Impact assessment results for the material extraction stage.

		2009 Baseline	Alt. (CA)	BW Variant	CSD Variant
Products					
Crude Oil for Feedstock	kg	0.645	0.577	17.00	26.31
Natural Gas for Feedstock	kg	0.389	0.361	10.48	15.09
GaBi Inventory Metrics					
Net primary energy from renewable materials	MJ	1.880E-02	1.704E-02	4.993E-01	7.533E-01
Gross primary energy from resources	MJ	5.047E+01	4.582E+01	1.342E+03	2.018E+03
Net primary energy from resources	MJ	4.651E+01	4.221E+01	1.236E+03	1.861E+03
Impact Indicators, in kg					
CML2001 - Nov. '09					
Acidification Potential	SO2-eq	1.121E-03	1.016E-03	2.978E-02	4.491E-02
Eutrophication Potential	P-eq	1.105E-04	9.995E-05	2.931E-03	4.436E-03
Freshwater Aquatic Ecotoxicity Potential	DCB-eq	7.641E-01	6.870E-01	2.020E+01	3.094E+01
Global Warming Potential (100 years)	CO_2-eq	2.929E-01	2.671E-01	7.807E+00	1.165E+01
Human Toxicity Potential	DCB-eq	2.112E+00	1.899E+00	5.583E+01	8.553E+01
Marine Aquatic Ecotoxicity Potential	DCB-eq	2.819E+03	2.535E+03	7.452E+04	1.141E+05
Ozone Layer Depletion Potential (steady state)	R11-eq	6.042E-11	5.409E-11	1.593E-09	2.460E-09
Photochem. Ozone Creation Potential	C2H4-eq	1.197E-04	1.089E-04	3.186E-03	4.774E-03
Terrestric Ecotoxicity Potential	DCB-eq	5.861E-05	5.288E-05	1.552E-03	2.362E-03
TRACI 2002					
Ecotoxcity Air	2,4-DCP-eq	1.815E-04	1.644E-04	4.819E-03	7.277E-03
Ecotoxcity Ground-Surface Soil	Benz.-eq	1.259E-06	1.126E-06	3.317E-05	5.128E-05
Ecotoxcity Water	2,4-DCP-eq	5.862E-01	5.272E-01	1.550E+01	2.373E+01
Eutrophication	N-eq	1.262E-04	1.142E-04	3.348E-03	5.066E-03
Human Health Cancer Air	Benz.-eq	2.400E-05	2.175E-05	6.374E-04	9.618E-04
Human Health Cancer Ground-Surface Soil	Benz.-eq	6.636E-09	5.941E-09	1.750E-07	2.702E-07
Human Health Cancer Water	Benz.-eq	3.654E-03	3.278E-03	9.646E-02	1.484E-01
Human Health Criteria Air-Point Source	PM2,5-eq	2.811E-04	2.548E-04	7.466E-03	1.126E-02
Human Health Non Cancer Air	Tolu.-eq	1.150E-02	1.041E-02	3.052E-01	4.609E-01
Human Health Non Cancer Ground-Surface Soil	Tolu.-eq	4.167E-05	3.729E-05	1.098E-03	1.697E-03
Human Health Non Cancer Water	Tolu.-eq	1.096E+02	9.827E+01	2.892E+03	4.458E+03
Smog Air	NOx-eq	2.415E-07	2.191E-07	6.416E-06	9.664E-06

Table C.3 Impact assessment results for the polymer production stage.

		2009 Baseline	Alt. (CA)	BW Variant	CSD Variant
Products					
PET Resin	kg	0.961	0.850	25.16	39.74
PP Resin	kg	0.143	0.143	4.03	4.94
GaBi Inventory Metrics					
Net primary energy from renewable materials	MJ	4.086E-01	3.640E-01	1.074E+01	1.674E+01
Gross primary energy from resources	MJ	3.625E+01	3.230E+01	9.530E+02	1.485E+03
Net primary energy from resources	MJ	3.379E+01	3.011E+01	8.883E+02	1.384E+03
Impact Indicators, in kg					
CML2001 - Nov. '09					
Acidification Potential	SO2-eq	2.972E-02	2.683E-02	7.874E-01	1.197E+00
Eutrophication Potential	P-eq	1.060E-03	9.431E-04	2.784E-02	4.347E-02
Freshwater Aquatic Ecotoxicity Potential	DCB-eq	2.300E-01	2.047E-01	6.042E+00	9.437E+00
Global Warming Potential (100 years)	CO_2-eq	2.329E+00	2.075E+00	6.122E+01	9.549E+01
Human Toxicity Potential	DCB-eq	1.139E+00	1.012E+00	2.990E+01	4.685E+01
Marine Aquatic Ecotoxicity Potential	DCB-eq	1.666E+03	1.483E+03	4.376E+04	6.832E+04
Ozone Layer Depletion Potential (steady state)	R11-eq	1.539E-09	1.363E-09	4.031E-08	6.352E-08
Photochem. Ozone Creation Potential	C2H4-eq	5.012E-03	4.469E-03	1.318E-01	2.051E-01
Terrestric Ecotoxicity Potential	DCB-eq	1.561E-03	1.385E-03	4.094E-02	6.425E-02
TRACI 2002					
Ecotoxcity Air	2,4-DCP-eq	8.515E-03	7.562E-03	2.234E-01	3.503E-01
Ecotoxcity Ground-Surface Soil	Benz.-eq	1.699E-06	1.512E-06	4.464E-05	6.970E-05
Ecotoxcity Water	2,4-DCP-eq	2.265E-01	2.016E-01	5.950E+00	9.294E+00
Eutrophication	N-eq	5.819E-04	5.175E-04	1.528E-02	2.390E-02
Human Health Cancer Air	Benz.-eq	8.957E-04	7.958E-04	2.351E-02	3.683E-02
Human Health Cancer Ground-Surface Soil	Benz.-eq	1.659E-08	1.477E-08	4.359E-07	6.806E-07
Human Health Cancer Water	Benz.-eq	1.150E-03	1.023E-03	3.020E-02	4.721E-02
Human Health Criteria Air-Point Source	PM2,5-eq	7.794E-03	7.014E-03	2.061E-01	3.152E-01
Human Health Non Cancer Air	Tolu.-eq	4.629E-01	4.113E-01	1.215E+01	1.903E+01
Human Health Non Cancer Ground-Surface Soil	Tolu.-eq	7.825E-05	6.965E-05	2.056E-03	3.210E-03
Human Health Non Cancer Water	Tolu.-eq	3.308E+01	2.942E+01	8.688E+02	1.359E+03
Smog Air	NOx-eq	6.763E-06	6.025E-06	1.778E-04	2.772E-04

Table C.4 Impact assessment results for the beverage manufacture stage.

		2009 Baseline	Alt. (CA)	BW Variant	CSD Variant
Products					
Beverage Delivered	L	27.9	27.9	1000.	1000.
GaBi Inventory Metrics					
Net primary energy from renewable materials	MJ	2.487E+00	2.486E+00	6.781E+01	9.955E+01
Gross primary energy from resources	MJ	4.299E+01	4.215E+01	1.199E+03	1.697E+03
Net primary energy from resources	MJ	4.057E+01	3.979E+01	1.131E+03	1.602E+03
Impact Indicators, in kg					
CML2001 - Nov. '09					
Acidification Potential	SO2-eq	2.079E-02	2.045E-02	5.778E-01	8.210E-01
Eutrophication Potential	P-eq	1.840E-03	1.770E-03	5.227E-02	7.264E-02
Freshwater Aquatic Ecotoxicity Potential	DCB-eq	3.201E-01	3.030E-01	9.306E+00	1.246E+01
Global Warming Potential (100 years)	CO_2-eq	2.466E+00	2.410E+00	6.906E+01	9.721E+01
Human Toxicity Potential	DCB-eq	1.130E+00	1.081E+00	3.244E+01	4.424E+01
Marine Aquatic Ecotoxicity Potential	DCB-eq	2.635E+03	2.570E+03	7.401E+04	1.042E+05
Ozone Layer Depletion Potential (steady state)	R11-eq	1.675E-09	1.671E-09	4.442E-08	6.869E-08
Photochem. Ozone Creation Potential	C2H4-eq	2.179E-03	2.132E-03	6.091E-02	8.610E-02
Terrestric Ecotoxicity Potential	DCB-eq	1.212E-03	1.208E-03	3.314E-02	4.841E-02
TRACI 2002					
Ecotoxcity Air	2,4-DCP-eq	3.516E-03	3.473E-03	9.749E-02	1.393E-01
Ecotoxcity Ground-Surface Soil	Benz.-eq	8.248E-06	8.207E-06	2.212E-04	3.355E-04
Ecotoxcity Water	2,4-DCP-eq	2.911E-01	2.777E-01	8.373E+00	1.139E+01
Eutrophication	N-eq	8.499E-04	8.242E-04	2.379E-02	3.381E-02
Human Health Cancer Air	Benz.-eq	8.853E-04	8.831E-04	2.419E-02	3.538E-02
Human Health Cancer Ground-Surface Soil	Benz.-eq	3.553E-07	3.551E-07	9.362E-06	1.463E-05
Human Health Cancer Water	Benz.-eq	1.883E-03	1.781E-03	5.478E-02	7.350E-02
Human Health Criteria Air-Point Source	PM2,5-eq	7.676E-03	7.451E-03	2.167E-01	3.022E-01
Human Health Non Cancer Air	Tolu.-eq	3.583E-01	3.571E-01	9.803E+00	1.431E+01
Human Health Non Cancer Ground-Surface Soil	Tolu.-eq	1.149E-03	1.148E-03	3.035E-02	4.723E-02
Human Health Non Cancer Water	Tolu.-eq	5.675E+01	5.359E+01	1.654E+03	2.214E+03
Smog Air	NOx-eq	1.307E-05	1.254E-05	3.742E-04	5.135E-04

Table C.5 Impact assessment results for the use and disposal stage.

		2009 Baseline	Alt. (CA)	BW Variant	CSD Variant
Products					
PET Bottle, at disposal in Recycling	kg	0.818	0.818	21.61	33.10
GaBi Inventory Metrics					
Net primary energy from renewable materials	MJ	2.089E-03	2.089E-03	5.521E-02	8.458E-02
Gross primary energy from resources	MJ	3.581E-01	3.581E-01	9.466E+00	1.450E+01
Net primary energy from resources	MJ	3.350E-01	3.350E-01	8.855E+00	1.357E+01
Impact Indicators, in kg					
CML2001 - Nov. '09					
Acidification Potential	SO2-eq	1.807E-04	1.807E-04	4.775E-03	7.316E-03
Eutrophication Potential	P-eq	3.826E-03	3.826E-03	1.011E-01	1.549E-01
Freshwater Aquatic Ecotoxicity Potential	DCB-eq	7.226E-03	7.226E-03	1.910E-01	2.926E-01
Global Warming Potential (100 years)	CO_2-eq	4.169E-02	4.169E-02	1.102E+00	1.688E+00
Human Toxicity Potential	DCB-eq	1.683E-02	1.683E-02	4.448E-01	6.815E-01
Marine Aquatic Ecotoxicity Potential	DCB-eq	2.282E+01	2.282E+01	6.030E+02	9.238E+02
Ozone Layer Depletion Potential (steady state)	R11-eq	9.391E-10	9.391E-10	2.482E-08	3.802E-08
Photochem. Ozone Creation Potential	C2H4-eq	2.410E-05	2.410E-05	6.371E-04	9.760E-04
Terrestric Ecotoxicity Potential	DCB-eq	2.868E-05	2.868E-05	7.580E-04	1.161E-03
TRACI 2002					
Ecotoxcity Air	2,4-DCP-eq	1.056E-04	1.056E-04	2.791E-03	4.275E-03
Ecotoxcity Ground-Surface Soil	Benz.-eq	1.366E-05	1.366E-05	3.611E-04	5.531E-04
Ecotoxcity Water	2,4-DCP-eq	1.991E-01	1.991E-01	5.262E+00	8.062E+00
Eutrophication	N-eq	3.560E-03	3.560E-03	9.409E-02	1.441E-01
Human Health Cancer Air	Benz.-eq	3.695E-06	3.695E-06	9.766E-05	1.496E-04
Human Health Cancer Ground-Surface Soil	Benz.-eq	1.090E-07	1.090E-07	2.881E-06	4.414E-06
Human Health Cancer Water	Benz.-eq	7.774E-04	7.774E-04	2.055E-02	3.148E-02
Human Health Criteria Air-Point Source	PM2,5-eq	1.178E-04	1.178E-04	3.114E-03	4.771E-03
Human Health Non Cancer Air	Tolu.-eq	4.603E-03	4.603E-03	1.216E-01	1.864E-01
Human Health Non Cancer Ground-Surface Soil	Tolu.-eq	5.595E-04	5.595E-04	1.479E-02	2.266E-02
Human Health Non Cancer Water	Tolu.-eq	2.204E+01	2.204E+01	5.825E+02	8.924E+02
Smog Air	NOx-eq	2.959E-07	2.959E-07	7.822E-06	1.198E-05

Table C.6 Impact assessment results for the materials recovery stage.

		2009 Baseline	Alt. (CA)	BW Variant	CSD Variant
Products					
PET, Baled at processing facility	kg	0.733	0.733	19.42	30.14
GaBi Inventory Metrics					
Net primary energy from renewable materials	MJ	4.922E-02	4.922E-02	1.764E+00	1.661E+00
Gross primary energy from resources	MJ	2.151E+00	2.151E+00	6.219E+01	8.318E+01
Net primary energy from resources	MJ	2.020E+00	2.020E+00	5.845E+01	7.805E+01
Impact Indicators, in kg					
CML2001 - Nov. '09					
Acidification Potential	SO2-eq	7.308E-04	7.308E-04	2.205E-02	2.764E-02
Eutrophication Potential	P-eq	1.404E-03	1.404E-03	3.653E-02	4.967E-02
Freshwater Aquatic Ecotoxicity Potential	DCB-eq	3.330E-02	3.330E-02	8.901E-01	1.337E+00
Global Warming Potential (100 years)	CO_2-eq	1.453E-01	1.453E-01	4.123E+00	5.638E+00
Human Toxicity Potential	DCB-eq	1.031E-01	1.031E-01	2.795E+00	4.123E+00
Marine Aquatic Ecotoxicity Potential	DCB-eq	1.508E+02	1.508E+02	4.292E+03	5.884E+03
Ozone Layer Depletion Potential (steady state)	R11-eq	5.442E-10	5.442E-10	1.431E-08	2.072E-08
Photochem. Ozone Creation Potential	C2H4-eq	1.042E-04	1.042E-04	3.017E-03	4.017E-03
Terrestric Ecotoxicity Potential	DCB-eq	2.777E-04	2.777E-04	7.557E-03	1.117E-02
TRACI 2002					
Ecotoxcity Air	2,4-DCP-eq	2.613E-03	2.613E-03	6.965E-02	1.064E-01
Ecotoxcity Ground-Surface Soil	Benz.-eq	8.463E-06	8.463E-06	2.226E-04	3.255E-04
Ecotoxcity Water	2,4-DCP-eq	1.339E-01	1.339E-01	3.502E+00	4.867E+00
Eutrophication	N-eq	1.076E-03	1.076E-03	2.797E-02	3.796E-02
Human Health Cancer Air	Benz.-eq	5.949E-05	5.949E-05	1.732E-03	2.309E-03
Human Health Cancer Ground-Surface Soil	Benz.-eq	5.403E-08	5.403E-08	1.420E-06	2.031E-06
Human Health Cancer Water	Benz.-eq	7.989E-04	7.989E-04	2.087E-02	2.908E-02
Human Health Criteria Air-Point Source	PM2,5-eq	3.154E-04	3.154E-04	9.102E-03	1.221E-02
Human Health Non Cancer Air	Tolu.-eq	1.024E-01	1.024E-01	2.772E+00	4.139E+00
Human Health Non Cancer Ground-Surface Soil	Tolu.-eq	3.016E-04	3.016E-04	7.927E-03	1.145E-02
Human Health Non Cancer Water	Tolu.-eq	2.924E+01	2.924E+01	7.626E+02	1.058E+03
Smog Air	NOx-eq	5.997E-07	5.997E-07	1.680E-05	2.356E-05

Table C.7 Impact assessment results for the reclamation stage.

		2009 Baseline	Alt. (CA)	BW Variant	CSD Variant
Products					
R-PET, to foreign market	kg	0.440	0.000	11.65	18.08
R-PET, food-grade, to US non-bottle use	kg	0.040	0.237	1.08	1.64
R-PET, to US non-food use	kg	0.067	0.199	1.79	2.77
R-PET, food grade, closed-loop recycled	kg	0.039	0.150	1.02	1.61
Secondary Mixed Plastic Waste	kg	0.018	0.018	0.47	0.72
Aluminum Hydroxide	kg	0.0072	0.0072	0.19	0.29
GaBi Inventory Metrics					
Net primary energy from renewable materials	MJ	3.210E-01	3.179E-01	8.502E+00	1.320E+01
Gross primary energy from resources	MJ	8.335E+00	6.466E+00	2.208E+02	3.427E+02
Net primary energy from resources	MJ	7.790E+00	6.044E+00	2.063E+02	3.203E+02
Impact Indicators, in kg					
CML2001 - Nov. '09					
Acidification Potential	SO2-eq	4.993E-03	3.127E-03	1.322E-01	2.053E-01
Eutrophication Potential	P-eq	2.694E-03	2.332E-03	7.136E-02	1.108E-01
Freshwater Aquatic Ecotoxicity Potential	DCB-eq	6.365E-02	2.551E-02	1.686E+00	2.617E+00
Global Warming Potential (100 years)	CO_2-eq	5.064E-01	3.709E-01	1.341E+01	2.082E+01
Human Toxicity Potential	DCB-eq	2.184E-01	1.085E-01	5.786E+00	8.980E+00
Marine Aquatic Ecotoxicity Potential	DCB-eq	4.241E+02	2.794E+02	1.123E+04	1.743E+04
Ozone Layer Depletion Potential (steady state)	R11-eq	2.477E-09	2.468E-09	6.561E-08	1.018E-07
Photochem. Ozone Creation Potential	C2H4-eq	4.280E-04	2.656E-04	1.134E-02	1.760E-02
Terrestric Ecotoxicity Potential	DCB-eq	9.713E-04	9.623E-04	2.573E-02	3.993E-02
TRACI 2002					
Ecotoxcity Air	2,4-DCP-eq	1.674E-03	1.578E-03	4.434E-02	6.882E-02
Ecotoxcity Ground-Surface Soil	Benz.-eq	7.616E-05	7.607E-05	2.017E-03	3.131E-03
Ecotoxcity Water	2,4-DCP-eq	7.303E-01	7.005E-01	1.934E+01	3.002E+01
Eutrophication	N-eq	2.687E-03	2.559E-03	7.116E-02	1.104E-01
Human Health Cancer Air	Benz.-eq	1.789E-04	1.740E-04	4.737E-03	7.353E-03
Human Health Cancer Ground-Surface Soil	Benz.-eq	4.357E-07	4.353E-07	1.154E-05	1.791E-05
Human Health Cancer Water	Benz.-eq	2.010E-02	1.987E-02	5.324E-01	8.264E-01
Human Health Criteria Air-Point Source	PM2,5-eq	2.047E-03	9.266E-04	5.421E-02	8.414E-02
Human Health Non Cancer Air	Tolu.-eq	1.270E-01	1.242E-01	3.363E+00	5.220E+00
Human Health Non Cancer Ground-Surface Soil	Tolu.-eq	2.839E-03	2.836E-03	7.519E-02	1.167E-01
Human Health Non Cancer Water	Tolu.-eq	6.664E+02	6.593E+02	1.765E+04	2.739E+04
Smog Air	NOx-eq	3.801E-06	1.038E-06	1.007E-04	1.562E-04

Table C.8 Impacts that could be avoided if secondary PET displaces primary PET.

		2009 Baseline	Alt. (CA)	BW Variant	CSD Variant
Secondary PET produced:	kg	0.547	0.436	14.51	22.50
Inventory Indicators Avoided					
Gross Primary Energy Demand - Bren	MJ	39.4	31.4	1046	1621
Net Primary Energy Demand	MJ	36.5	29.1	968	1500
Gross Feedstock Energy	MJ	21.8	17.4	578	896
Net Feedstock Energy	MJ	20.2	16.1	535	829
Net Delivered Energy	MJ	11.9	9.5	315	488
Freight Services Provided	tkm	3.58	2.86	94.9	147.2
Net Transport Energy	MJ	0.81	0.65	21.5	33.4
Waste Disposal Provided	kg	0.05	0.04	1.4	2.1
GaBi Inventory Metrics					
Net primary energy from renewable materials	MJ	2.286E-01	1.823E-01	6.060E+00	9.395E+00
Gross primary energy from resources	MJ	4.246E+01	3.385E+01	1.126E+03	1.745E+03
Net primary energy from resources	MJ	3.940E+01	3.141E+01	1.045E+03	1.619E+03
Impact Indicators Avoided, in kg					
CML2001 - Nov. '09					
Acidification Potential	SO2-eq	1.478E-02	1.178E-02	3.917E-01	6.073E-01
Eutrophication Potential	P-eq	6.264E-04	4.994E-04	1.660E-02	2.574E-02
Freshwater Aquatic Ecotoxicity Potential	DCB-eq	5.049E-01	4.025E-01	1.339E+01	2.075E+01
Global Warming Potential (100 years)	CO_2-eq	1.385E+00	1.104E+00	3.671E+01	5.691E+01
Human Toxicity Potential	DCB-eq	1.678E+00	1.338E+00	4.449E+01	6.895E+01
Marine Aquatic Ecotoxicity Potential	DCB-eq	2.304E+03	1.837E+03	6.108E+04	9.467E+04
Ozone Layer Depletion Potential (steady state)	R11-eq	8.988E-10	7.166E-10	2.382E-08	3.693E-08
Photochem. Ozone Creation Potential	C2H4-eq	2.728E-03	2.175E-03	7.232E-02	1.121E-01
Terrestric Ecotoxicity Potential	DCB-eq	8.933E-04	7.122E-04	2.368E-02	3.671E-02
TRACI 2002					
Ecotoxcity Air	2,4-DCP-eq	4.784E-03	3.814E-03	1.268E-01	1.966E-01
Ecotoxcity Ground-Surface Soil	Benz.-eq	1.574E-06	1.255E-06	4.173E-05	6.468E-05
Ecotoxcity Water	2,4-DCP-eq	4.141E-01	3.301E-01	1.098E+01	1.701E+01
Eutrophication	N-eq	3.771E-04	3.007E-04	9.997E-03	1.550E-02
Human Health Cancer Air	Benz.-eq	5.038E-04	4.016E-04	1.335E-02	2.070E-02
Human Health Cancer Ground-Surface Soil	Benz.-eq	1.243E-08	9.909E-09	3.294E-07	5.107E-07
Human Health Cancer Water	Benz.-eq	2.482E-03	1.979E-03	6.582E-02	1.020E-01
Human Health Criteria Air-Point Source	PM2,5-eq	3.978E-03	3.172E-03	1.054E-01	1.635E-01
Human Health Non Cancer Air	Tolu.-eq	2.599E-01	2.072E-01	6.889E+00	1.068E+01
Human Health Non Cancer Ground-Surface Soil	Tolu.-eq	6.401E-05	5.103E-05	1.697E-03	2.630E-03
Human Health Non Cancer Water	Tolu.-eq	7.415E+01	5.911E+01	1.966E+03	3.047E+03
Smog Air	NOx-eq	3.754E-06	2.993E-06	9.949E-05	1.542E-04

Appendix D - Inventory and Impact Indicators for Support Processes

- Electricity Production (Infrastructure):
  - U.S. Average;
  - WECC Production Mix;
  - California Consumption Mix.

- Liquid Fuel (Infrastructure):
  - Diesel, at filling station;
  - Gasoline, at filling station;
  - Residual fuel oil, at refinery.

- Fuel Combustion for Heat Recovery (Infrastructure):
  - Natural gas, combusted in boiler;
  - Coal, combusted in boiler;
  - Diesel, combusted in boiler;
  - LP Gas, combusted in boiler;
  - Residual fuel oil, combusted in boiler.

- Fuel Combustion for mechanical work (Infrastructure):
  - Gasoline, combusted in equipment;

- Transportation:
  - Freight by train (U.S. LCI);
  - Freight by combination truck (Bren);
  - Freight by medium-heavy-duty truck (Bren);
  - Freight by ocean freighter (U.S. LCI);
  - Freight by barge (U.S. LCI);
  - Natural gas by pipeline (FAL);
  - Petroleum products by pipeline (FAL).

- Waste disposal (Ecoinvent):
  - Polyethylene, 0.4 percent water, to municipal incineration;
  - Polyethylene, 0.4 percent water, to sanitary landfill;
  - Polyethylene terephthalate, 0.2 percent water, to municipal incineration;
  - Polyethylene terephthalate, 0.2 percent water, to sanitary landfill;
  - Polypropylene, 15.9 percent water, to municipal incineration;
  - Polypropylene, 15.9 percent water, to sanitary landfill;
  - Plastics, mixture, 15.3 percent water, to sanitary landfill;
  - Refinery sludge, 89.5 percent water, to sanitary landfill.

- Water (PE International):
  - Potable water from groundwater;
  - Organic wastewater processing.

- Supplies (Ecoinvent):
  - Lubricating oil;
  - Baling wire 10AWG (custom);
  - Sodium hydroxide, 50 percent in H_2O, production mix.

Table D.1

		U.S.: Electricity Supply Mix – U.S. Average Bren	U.S.: Electricity Supply - WECC Production Mix Bren	U.S.: Electricity Supply - CA Consumption Mix Bren
	Source:	U.S. LCI / eGrid	U.S. LCI / eGrid	U.S. LCI / eGrid
	Output:	1 MJ	1 MJ	1 MJ
Inventory Indicators				
Gross Primary Energy Demand [MJ]		3.041E+00	2.894E+00	2.939E+00
Net Primary Energy Demand [MJ]		2.892E+00	2.753E+00	2.777E+00
Gross Feedstock Energy [MJ]		0.E+00	0.E+00	0.E+00
Net Feedstock Energy [MJ]		0.E+00	0.E+00	0.E+00
Net Delivered Energy [MJ]		1.E+00	1.E+00	1.E+00
Freight Services Provided [tkm]		1.045E+02	9.713E+01	1.009E+02
Net Transport Energy [MJ]		2.757E-02	2.551E-02	2.665E-02
Waste Disposal Provided [kg]		1.223E-02	7.838E-03	7.453E-03
GaBi Inventory Metrics				
Net primary energy from renewable raw materials	MJ	1.236E-01	2.976E-01	2.036E-01
Gross primary energy from resources	MJ	4.497E+00	3.431E+00	3.792E+00
Net primary energy from resources	MJ	4.313E+00	3.261E+00	3.602E+00
Impact Indicators				
CML2001 - Dec. '07				
Acidification Potential	kg SO2-Eq.	2.046E-03	1.755E-03	1.807E-03
Eutrophication Potential	kg P-Eq.	7.322E-05	5.842E-05	5.7E-05
Freshwater Aquatic Ecotoxicity Potential	kg DCB-Eq.	7.945E-03	6.652E-03	8.435E-03
Global Warming Potential (100 years)	kg CO_2-Eq.	2.157E-01	1.835E-01	1.891E-01
Human Toxicity Potential	kg DCB-Eq.	5.894E-02	4.571E-02	4.896E-02
Marine Aquatic Ecotoxicity Potential	kg DCB-Eq.	2.58E+02	1.966E+02	1.91E+02
Ozone Layer Depletion Potential (steady state)	kg R11-Eq.	2.692E-11	3.21E-11	2.344E-11
Photochem. Ozone Creation Potential	kg Ethene-Eq.	2.016E-04	1.699E-04	1.676E-04
Terrestric Ecotoxicity Potential	kg DCB-Eq.	1.729E-04	1.346E-04	1.246E-04
TRACI 2002				
Ecotoxcity Air	kg 2,4-DCP-Eq	5.707E-04	3.207E-04	3.397E-04
Ecotoxcity Ground-Surface Soil	kg Benzene-Eq.	2.133E-07	3.253E-07	2.128E-07
Ecotoxcity Water	kg 2,4-DCP-Eq	1.053E-02	8.035E-03	9.617E-03
Eutrophication	kg N-Eq.	2.759E-05	2.23E-05	2.21E-05
Human Health Cancer Air	kg Benzene-Eq.	1.372E-04	1.018E-04	9.546E-05
Human Health Cancer Ground-Surface Soil	kg Benzene-Eq.	2.589E-09	3.607E-09	2.454E-09
Human Health Cancer Water	kg Benzene-Eq.	4.821E-05	3.314E-05	3.897E-05
Human Health Criteria Air-Point Source	kg PM2,5-Eq.	5.876E-04	4.923E-04	4.977E-04
Human Health Non Cancer Air	kg Toluene-Eq.	5.49E-02	3.999E-02	3.78E-02
Human Health Non Cancer Ground-Surface Soil	kg Toluene-Eq.	1.128E-05	1.623E-05	1.089E-05
Human Health Non Cancer Water	kg Toluene-Eq.	1.375E+00	8.833E-01	1.031E+00
Smog Air	kg NOx-Eq.	7.63E-07	6.117E-07	5.859E-07

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Table D.1 continued

		Diesel at Filling Station	Gasoline at Filling Station	Residual Fuel Oil at Refinery
	Source:	**U.S. LCI**	**U.S. LCI**	**U.S. LCI**
	Output:	1kg	1kg	1kg
Inventory Indicators				
Gross Primary Energy Demand [MJ]		5.412E+01	5.261E+01	4.997E+01
Net Primary Energy Demand [MJ]		5.059E+01	4.918E+01	4.671E+01
Gross Feedstock Energy [MJ]		0.E+00	0.E+00	0.E+00
Net Feedstock Energy [MJ]		0.E+00	0.E+00	0.E+00
Net Delivered Energy [MJ]		4.304E+01	4.403E+01	4.044E+01
Freight Services Provided [tkm]		8.932E+02	9.002E+02	4.451E+02
Net Transport Energy [MJ]		3.131E-01	3.545E-01	1.951E-01
Waste Disposal Provided [kg]		4.506E-02	4.38E-02	4.144E-02
GaBi Inventory Metrics				
Net primary energy from renewable raw materials	MJ	9.19E-02	8.926E-02	8.276E-02
Gross primary energy from resources	MJ	5.566E+01	5.41E+01	5.137E+01
Net primary energy from resources	MJ	5.202E+01	5.057E+01	4.801E+01
Impact Indicators				
CML2001 - Dec. '07				
Acidification Potential	kg SO2-Eq.	6.346E-03	6.191E-03	5.799E-03
Eutrophication Potential	kg P-Eq.	3.082E-04	3.049E-04	2.762E-04
Freshwater Aquatic Ecotoxicity Potential	kg DCB-Eq.	1.135E+00	1.103E+00	1.049E+00
Global Warming Potential (100 years)	kg CO_2-Eq.	5.388E-01	5.272E-01	4.885E-01
Human Toxicity Potential	kg DCB-Eq.	3.171E+00	3.083E+00	2.93E+00
Marine Aquatic Ecotoxicity Potential	kg DCB-Eq.	4.307E+03	4.187E+03	3.977E+03
Ozone Layer Depletion Potential (steady state)	kg R11-Eq.	2.678E-10	2.608E-10	2.478E-10
Photochem. Ozone Creation Potential	kg Ethene-Eq.	1.034E-03	1.007E-03	9.485E-04
Terrestric Ecotoxicity Potential	kg DCB-Eq.	2.539E-04	2.467E-04	2.316E-04
TRACI 2002				
Ecotoxcity Air	kg 2,4-DCP-Eq	2.867E-03	2.786E-03	2.64E-03
Ecotoxcity Ground-Surface Soil	kg Benzene-Eq.	2.691E-06	2.616E-06	2.484E-06
Ecotoxcity Water	kg 2,4-DCP-Eq	8.877E-01	8.63E-01	8.204E-01
Eutrophication	kg N-Eq.	2.28E-04	2.234E-04	2.077E-04
Human Health Cancer Air	kg Benzene-Eq.	1.461E-04	1.419E-04	1.326E-04
Human Health Cancer Ground-Surface Soil	kg Benzene-Eq.	1.482E-08	1.44E-08	1.365E-08
Human Health Cancer Water	kg Benzene-Eq.	6.771E-03	6.583E-03	6.258E-03
Human Health Criteria Air-Point Source	kg PM2,5-Eq.	1.733E-03	1.701E-03	1.568E-03
Human Health Non Cancer Air	kg Toluene-Eq.	8.158E-02	7.925E-02	7.443E-02
Human Health Non Cancer Ground-Surface Soil	kg Toluene-Eq.	9.09E-05	8.836E-05	8.382E-05
Human Health Non Cancer Water	kg Toluene-Eq.	2.096E+02	2.038E+02	1.937E+02
Smog Air	kg NOx-Eq.	1.705E-06	1.696E-06	1.504E-06

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Table D.1 continued

		Natural Gas, Combusted in Boiler	Coal, Combusted in Boiler	Diesel, Combusted in Boiler
	Source:	**U.S. LCI**	**U.S. LCI**	**U.S. LCI**
	Output:	1m3	1kg	1m3
Inventory Indicators				
Gross Primary Energy Demand [MJ]		4.395E+01	2.923E+01	4.527E+04
Net Primary Energy Demand [MJ]		3.968E+01	2.83E+01	4.232E+04
Gross Feedstock Energy [MJ]		0.E+00	0.E+00	0.E+00
Net Feedstock Energy [MJ]		0.E+00	0.E+00	0.E+00
Net Delivered Energy [MJ]		3.557E+01	2.7E+01	3.598E+04
Freight Services Provided [tkm]		1.503E+03	1.21E+03	7.821E+05
Net Transport Energy [MJ]		4.102E-01	3.092E-01	2.142E+02
Waste Disposal Provided [kg]		2.416E-02	1.436E-01	3.772E+01
GaBi Inventory Metrics				
Net primary energy from renewable raw materials	MJ	3.04E-02	2.584E-02	7.714E+01
Gross primary energy from resources	MJ	4.432E+01	3.724E+01	4.656E+04
Net primary energy from resources	MJ	4.004E+01	3.573E+01	4.352E+04
Impact Indicators				
CML2001 - Dec. '07				
Acidification Potential	kg SO2-Eq.	2.422E-02	2.388E-02	7.521E+00
Eutrophication Potential	kg P-Eq.	3.374E-04	9.785E-04	6.285E-01
Freshwater Aquatic Ecotoxicity Potential	kg DCB-Eq.	2.431E-01	2.169E-02	9.501E+02
Global Warming Potential (100 years)	kg CO_2-Eq.	2.433E+00	2.968E+00	3.175E+03
Human Toxicity Potential	kg DCB-Eq.	6.856E-01	5.552E-01	2.715E+03
Marine Aquatic Ecotoxicity Potential	kg DCB-Eq.	9.39E+02	2.261E+03	3.632E+06
Ozone Layer Depletion Potential (steady state)	kg R11-Eq.	9.021E-12	3.756E-08	2.24E-07
Photochem. Ozone Creation Potential	kg Ethene-Eq.	1.32E-03	1.199E-03	9.949E-01
Terrestric Ecotoxicity Potential	kg DCB-Eq.	2.593E-04	1.94E-02	1.998E+00
TRACI 2002				
Ecotoxcity Air	kg 2,4-DCP-Eq	5.257E-04	3.927E-03	6.056E+00
Ecotoxcity Ground-Surface Soil	kg Benzene-Eq.	7.699E-08	4.227E-06	2.251E-03
Ecotoxcity Water	kg 2,4-DCP-Eq	1.94E-01	9.876E-02	7.429E+02
Eutrophication	kg N-Eq.	1.772E-04	3.459E-04	3.17E-01
Human Health Cancer Air	kg Benzene-Eq.	6.709E-05	1.536E-03	7.015E-01
Human Health Cancer Ground-Surface Soil	kg Benzene-Eq.	7.615E-10	5.908E-08	1.24E-05
Human Health Cancer Water	kg Benzene-Eq.	6.775E-04	5.164E-04	5.663E+00
Human Health Criteria Air-Point Source	kg PM2,5-Eq.	5.502E-03	8.143E-03	2.671E+00
Human Health Non Cancer Air	kg Toluene-Eq.	4.678E-02	4.192E+00	4.842E+02
Human Health Non Cancer Ground-Surface Soil	kg Toluene-Eq.	3.572E-06	2.456E-04	7.605E-02
Human Health Non Cancer Water	kg Toluene-Eq.	1.497E+01	1.508E+01	1.753E+05
Smog Air	kg NOx-Eq.	2.269E-06	6.605E-06	4.286E-03

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Table D.1 continued

		LP Gas, Combusted in Boiler	Residual Fuel Oil, Combusted in Boiler	Gasoline, Combusted in Equipment
	Source:	**U.S. LCI**	**U.S. LCI**	**U.S. LCI**
	Output:	1m3	1m3	1m3
Inventory Indicators				
Gross Primary Energy Demand [MJ]		2.831E+04	4.925E+04	3.858E+04
Net Primary Energy Demand [MJ]		2.647E+04	4.604E+04	3.606E+04
Gross Feedstock Energy [MJ]		0.E+00	0.E+00	0.E+00
Net Feedstock Energy [MJ]		0.E+00	0.E+00	0.E+00
Net Delivered Energy [MJ]		2.503E+04	3.984E+04	3.227E+04
Freight Services Provided [tkm]		5.188E+05	4.757E+05	6.782E+05
Net Transport Energy [MJ]		1.42E+02	2.113E+02	1.857E+02
Waste Disposal Provided [kg]		2.36E+01	4.211E+01	3.214E+01
GaBi Inventory Metrics				
Net primary energy from renewable raw materials	MJ	4.837E+01	8.156E+01	6.572E+01
Gross primary energy from resources	MJ	2.912E+04	5.062E+04	3.968E+04
Net primary energy from resources	MJ	2.722E+04	4.731E+04	3.709E+04
Impact Indicators				
CML2001 - Dec. '07				
Acidification Potential	kg SO2-Eq.	4.617E+00	1.544E+01	2.185E+01
Eutrophication Potential	kg P-Eq.	5.294E-01	1.193E+00	4.584E+00
Freshwater Aquatic Ecotoxicity Potential	kg DCB-Eq.	5.934E+02	1.041E+03	8.097E+02
Global Warming Potential (100 years)	kg CO_2-Eq.	2.041E+03	3.753E+03	2.529E+03
Human Toxicity Potential	kg DCB-Eq.	1.662E+03	3.335E+03	2.329E+03
Marine Aquatic Ecotoxicity Potential	kg DCB-Eq.	2.253E+06	3.965E+06	3.071E+06
Ozone Layer Depletion Potential (steady state)	kg R11-Eq.	1.403E-07	2.442E-07	1.913E-07
Photochem. Ozone Creation Potential	kg Ethene-Eq.	6.372E-01	1.408E+00	6.178E+00
Terrestric Ecotoxicity Potential	kg DCB-Eq.	1.335E-01	2.447E+00	2.317E-01
TRACI 2002				
Ecotoxcity Air	kg 2,4-DCP-Eq	1.505E+00	8.247E+01	2.055E+00
Ecotoxcity Ground-Surface Soil	kg Benzene-Eq.	1.408E-03	2.447E-03	1.918E-03
Ecotoxcity Water	kg 2,4-DCP-Eq	4.643E+02	8.09E+02	6.328E+02
Eutrophication	kg N-Eq.	2.338E-01	5.169E-01	1.644E+00
Human Health Cancer Air	kg Benzene-Eq.	7.679E-02	1.509E+00	1.187E-01
Human Health Cancer Ground-Surface Soil	kg Benzene-Eq.	7.757E-06	1.345E-05	1.057E-05
Human Health Cancer Water	kg Benzene-Eq.	3.542E+00	6.167E+00	4.826E+00
Human Health Criteria Air-Point Source	kg PM2,5-Eq.	1.866E+00	5.41E+00	1.332E+01
Human Health Non Cancer Air	kg Toluene-Eq.	4.286E+01	1.324E+03	6.186E+01
Human Health Non Cancer Ground-Surface Soil	kg Toluene-Eq.	4.757E-02	8.26E-02	6.481E-02
Human Health Non Cancer Water	kg Toluene-Eq.	1.096E+05	1.909E+05	1.494E+05
Smog Air	kg NOx-Eq.	3.487E-03	8.548E-03	3.663E-02

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Table D.1 continued

		Transport, Train	Transport, Single unit truck	Transport, Combination Truck
	Source:	**U.S. LCI**	**EMFAC**	**EMFAC**
	Output:	1 tkm	1 tkm	1 tkm
Inventory Indicators				
Gross Primary Energy Demand [MJ]		2.932E-01	5.931E+00	1.997E+00
Net Primary Energy Demand [MJ]		2.741E-01	5.545E+00	1.867E+00
Gross Feedstock Energy [MJ]		0.E+00	0.E+00	0.E+00
Net Feedstock Energy [MJ]		0.E+00	0.E+00	0.E+00
Net Delivered Energy [MJ]		2.332E-01	4.717E+00	1.588E+00
Freight Services Provided [tkm]		1.005E+03	1.098E+03	1.033E+03
Net Transport Energy [MJ]		2.345E-01	4.743E+00	1.597E+00
Waste Disposal Provided [kg]		2.442E-04	4.939E-03	1.663E-03
GaBi Inventory Metrics				
Net primary energy from renewable raw materials	MJ	4.98E-04	1.007E-02	3.391E-03
Gross primary energy from resources	MJ	3.016E-01	6.1E+00	2.054E+00
Net primary energy from resources	MJ	2.819E-01	5.701E+00	1.92E+00
Impact Indicators				
CML2001 - Dec. '07				
Acidification Potential	kg SO2-Eq.	2.885E-04	2.841E-03	8.518E-04
Eutrophication Potential	kg P-Eq.	6.657E-05	5.922E-04	1.721E-04
Freshwater Aquatic Ecotoxicity Potential	kg DCB-Eq.	6.149E-03	1.244E-01	4.187E-02
Global Warming Potential (100 years)	kg CO_2-Eq.	2.2E-02	4.104E-01	1.376E-01
Human Toxicity Potential	kg DCB-Eq.	1.779E-02	3.528E-01	1.185E-01
Marine Aquatic Ecotoxicity Potential	kg DCB-Eq.	2.334E+01	4.721E+02	1.589E+02
Ozone Layer Depletion Potential (steady state)	kg R11-Eq.	1.451E-12	2.935E-11	9.882E-12
Photochem. Ozone Creation Potential	kg Ethene-Eq.	2.78E-05	3.088E-04	1.143E-04
Terrestric Ecotoxicity Potential	kg DCB-Eq.	1.48E-06	2.869E-05	9.861E-06
TRACI 2002				
Ecotoxcity Air	kg 2,4-DCP-Eq	1.554E-05	3.142E-04	1.058E-04
Ecotoxcity Ground-Surface Soil	kg Benzene-Eq.	1.458E-08	2.949E-07	9.93E-08
Ecotoxcity Water	kg 2,4-DCP-Eq	4.81E-03	9.729E-02	3.276E-02
Eutrophication	kg N-Eq.	2.33E-05	2.147E-04	6.3E-05
Human Health Cancer Air	kg Benzene-Eq.	7.914E-07	1.601E-05	5.39E-06
Human Health Cancer Ground-Surface Soil	kg Benzene-Eq.	8.029E-11	1.624E-09	5.468E-10
Human Health Cancer Water	kg Benzene-Eq.	3.669E-05	7.421E-04	2.499E-04
Human Health Criteria Air-Point Source	kg PM2,5-Eq.	1.936E-04	1.754E-03	5.526E-04
Human Health Non Cancer Air	kg Toluene-Eq.	4.42E-04	8.941E-03	3.01E-03
Human Health Non Cancer Ground-Surface Soil	kg Toluene-Eq.	4.925E-07	9.962E-06	3.354E-06
Human Health Non Cancer Water	kg Toluene-Eq.	1.136E+00	2.297E+01	7.735E+00
Smog Air	kg NOx-Eq.	5.081E-07	4.48E-06	1.3E-06

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Table D.1 continued

		Transport, Ocean Freighter	Transport, Barge	Transport, Natural Gas Pipeline
	Source:	**U.S. LCI**	**U.S. LCI**	**ACC 2007**
	Output:	1 tkm	1 tkm	1 tkm
Inventory Indicators				
Gross Primary Energy Demand [MJ]		2.405E-01	4.34E-01	5.951E-01
Net Primary Energy Demand [MJ]		2.248E-01	4.056E-01	5.371E-01
Gross Feedstock Energy [MJ]		0.E+00	0.E+00	0.E+00
Net Feedstock Energy [MJ]		0.E+00	0.E+00	0.E+00
Net Delivered Energy [MJ]		1.943E-01	3.498E-01	4.76E-01
Freight Services Provided [tkm]		1.002E+03	1.004E+03	1.02E+03
Net Transport Energy [MJ]		1.953E-01	3.516E-01	4.884E-01
Waste Disposal Provided [kg]		1.995E-04	3.602E-04	3.18E-04
GaBi Inventory Metrics				
Net primary energy from renewable raw materials	MJ	3.993E-04	7.227E-04	3.062E-04
Gross primary energy from resources	MJ	2.473E-01	4.461E-01	5.988E-01
Net primary energy from resources	MJ	2.311E-01	4.17E-01	5.408E-01
Impact Indicators				
CML2001 - Dec. '07				
Acidification Potential	kg SO2-Eq.	2.982E-04	3.142E-04	3.278E-04
Eutrophication Potential	kg P-Eq.	5.743E-05	4.873E-05	4.577E-06
Freshwater Aquatic Ecotoxicity Potential	kg DCB-Eq.	5.048E-03	9.105E-03	3.301E-03
Global Warming Potential (100 years)	kg CO_2-Eq.	1.842E-02	3.311E-02	3.295E-02
Human Toxicity Potential	kg DCB-Eq.	1.463E-02	2.588E-02	9.217E-03
Marine Aquatic Ecotoxicity Potential	kg DCB-Eq.	1.914E+01	3.454E+01	1.254E+01
Ozone Layer Depletion Potential (steady state)	kg R11-Eq.	1.193E-12	2.151E-12	9.934E-14
Photochem. Ozone Creation Potential	kg Ethene-Eq.	2.42E-05	2.606E-05	1.731E-05
Terrestric Ecotoxicity Potential	kg DCB-Eq.	1.179E-06	2.069E-06	8.498E-07
TRACI 2002				
Ecotoxcity Air	kg 2,4-DCP-Eq	1.271E-05	2.294E-05	2.748E-06
Ecotoxcity Ground-Surface Soil	kg Benzene-Eq.	1.195E-08	2.157E-08	8.62E-10
Ecotoxcity Water	kg 2,4-DCP-Eq	3.948E-03	7.123E-03	2.629E-03
Eutrophication	kg N-Eq.	2.008E-05	1.754E-05	2.404E-06
Human Health Cancer Air	kg Benzene-Eq.	6.391E-07	1.156E-06	3.937E-07
Human Health Cancer Ground-Surface Soil	kg Benzene-Eq.	6.571E-11	1.186E-10	8.111E-12
Human Health Cancer Water	kg Benzene-Eq.	3.012E-05	5.433E-05	9.172E-06
Human Health Criteria Air-Point Source	kg PM2,5-Eq.	1.77E-04	1.615E-04	7.435E-05
Human Health Non Cancer Air	kg Toluene-Eq.	3.586E-04	6.48E-04	1.848E-04
Human Health Non Cancer Ground-Surface Soil	kg Toluene-Eq.	4.035E-07	7.281E-07	3.881E-08
Human Health Non Cancer Water	kg Toluene-Eq.	9.323E-01	1.682E+00	2.024E-01
Smog Air	kg NOx-Eq.	4.387E-07	3.688E-07	3.07E-08

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Table D.1 continued

		Transport, Pipeline, petroleum products	CH: disposal, polyethylene, 0.4% water, to municipal incineration	CH: disposal, polyethylene, 0.4% water, to sanitary landfill
	Source:	**ACC 2007**	**Ecoinvent**	**Ecoinvent**
	Output:	1 tkm	1 kg	1 kg
Inventory Indicators				
Gross Primary Energy Demand [MJ]		1.634E-01		
Net Primary Energy Demand [MJ]		1.555E-01		
Gross Feedstock Energy [MJ]		0.E+00		
Net Feedstock Energy [MJ]		0.E+00		
Net Delivered Energy [MJ]		0.E+00		
Freight Services Provided [tkm]		1.006E+03		
Net Transport Energy [MJ]		5.524E-02		
Waste Disposal Provided [kg]		6.574E-04	1.E+00	1.E+00
GaBi Inventory Metrics				
Net primary energy from renewable raw materials	MJ	6.645E-03	3.729E-03	4.639E-03
Gross primary energy from resources	MJ	2.418E-01	2.384E-01	3.242E-01
Net primary energy from resources	MJ	2.318E-01	2.215E-01	3.036E-01
Impact Indicators				
CML2001 - Dec. '07				
Acidification Potential	kg SO2-Eq.	1.1E-04	2.339E-04	7.188E-05
Eutrophication Potential	kg P-Eq.	3.936E-06	1.127E-03	1.85E-02
Freshwater Aquatic Ecotoxicity Potential	kg DCB-Eq.	4.271E-04	1.612E-02	1.079E-02
Global Warming Potential (100 years)	kg CO_2-Eq.	1.159E-02	2.996E+00	1.125E-01
Human Toxicity Potential	kg DCB-Eq.	3.169E-03	8.489E-02	6.679E-03
Marine Aquatic Ecotoxicity Potential	kg DCB-Eq.	1.387E+01	3.559E+01	1.38E+01
Ozone Layer Depletion Potential (steady state)	kg R11-Eq.	1.447E-12	1.57E-09	3.092E-09
Photochem. Ozone Creation Potential	kg Ethene-Eq.	1.083E-05	4.522E-05	3.277E-05
Terrestric Ecotoxicity Potential	kg DCB-Eq.	9.295E-06	3.181E-04	8.492E-05
TRACI 2002				
Ecotoxcity Air	kg 2,4-DCP-Eq	3.068E-05	3.913E-04	2.995E-04
Ecotoxcity Ground-Surface Soil	kg Benzene-Eq.	1.146E-08	2.027E-05	4.208E-05
Ecotoxcity Water	kg 2,4-DCP-Eq	5.662E-04	8.407E-01	1.432E+00
Eutrophication	kg N-Eq.	1.483E-06	1.391E-03	1.456E-02
Human Health Cancer Air	kg Benzene-Eq.	7.376E-06	2.379E-03	9.306E-06
Human Health Cancer Ground-Surface Soil	kg Benzene-Eq.	1.392E-10	1.497E-07	3.596E-07
Human Health Cancer Water	kg Benzene-Eq.	2.592E-06	1.142E-03	8.427E-03
Human Health Criteria Air-Point Source	kg PM2,5-Eq.	3.159E-05	1.7E-04	5.093E-05
Human Health Non Cancer Air	kg Toluene-Eq.	2.951E-03	2.682E+00	1.361E-02
Human Health Non Cancer Ground-Surface Soil	kg Toluene-Eq.	6.061E-07	7.936E-04	1.792E-03
Human Health Non Cancer Water	kg Toluene-Eq.	7.39E-02	2.118E+01	3.248E+02
Smog Air	kg NOx-Eq.	4.101E-08	3.942E-07	1.114E-07

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Table D.1 continued

		CH: Disposal, polyethylene terephtalate, 0.2% water, to municipal incineration	CH: Disposal, polyethylene terephtalate, 0.2% water, to sanitary landfill	CH: Disposal, polypropylene, 15.9% water, to municipal incineration
	Source:	**Ecoinvent**	**Ecoinvent**	**Ecoinvent**
	Output:	1 kg	1 kg	1 kg
Inventory Indicators				
Waste Disposal Provided [kg]		1.E+00	1.E+00	1.E+00
GaBi Inventory Metrics				
Net primary energy from renewable raw materials	MJ	2.824E-03	5.496E-03	3.366E-03
Gross primary energy from resources	MJ	2.449E-01	3.294E-01	2.249E-01
Net primary energy from resources	MJ	2.262E-01	3.088E-01	2.089E-01
Impact Indicators				
CML2001 - Dec. '07				
Acidification Potential	kg SO2-Eq.	3.17E-04	7.225E-05	2.274E-04
Eutrophication Potential	kg P-Eq.	8.136E-04	1.254E-02	9.58E-04
Freshwater Aquatic Ecotoxicity Potential	kg DCB-Eq.	1.141E-02	6.454E-03	1.364E-02
Global Warming Potential (100 years)	kg CO_2-Eq.	2.033E+00	8.E-02	2.535E+00
Human Toxicity Potential	kg DCB-Eq.	3.493E-01	5.55E-03	7.503E-02
Marine Aquatic Ecotoxicity Potential	kg DCB-Eq.	3.042E+01	9.282E+00	3.024E+01
Ozone Layer Depletion Potential (steady state)	kg R11-Eq.	1.727E-09	3.101E-09	1.494E-09
Photochem. Ozone Creation Potential	kg Ethene-Eq.	4.939E-05	2.661E-05	4.473E-05
Terrestric Ecotoxicity Potential	kg DCB-Eq.	2.389E-04	9.033E-05	2.855E-04
TRACI 2002				
Ecotoxcity Air	kg 2,4-DCP-Eq	3.412E-04	3.05E-04	3.675E-04
Ecotoxcity Ground-Surface Soil	kg Benzene-Eq.	1.68E-05	4.514E-05	1.884E-05
Ecotoxcity Water	kg 2,4-DCP-Eq	5.528E-01	6.448E-01	7.301E-01
Eutrophication	kg N-Eq.	1.017E-03	1.173E-02	1.175E-03
Human Health Cancer Air	kg Benzene-Eq.	2.377E-03	9.788E-06	2.378E-03
Human Health Cancer Ground-Surface Soil	kg Benzene-Eq.	1.543E-07	3.603E-07	1.414E-07
Human Health Cancer Water	kg Benzene-Eq.	7.285E-04	2.467E-03	9.742E-04
Human Health Criteria Air-Point Source	kg PM2,5-Eq.	2.23E-04	5.125E-05	1.646E-04
Human Health Non Cancer Air	kg Toluene-Eq.	2.662E+00	1.392E-02	2.674E+00
Human Health Non Cancer Ground-Surface Soil	kg Toluene-Eq.	7.495E-04	1.849E-03	7.443E-04
Human Health Non Cancer Water	kg Toluene-Eq.	7.142E+00	6.967E+01	1.816E+01
Smog Air	kg NOx-Eq.	5.548E-07	1.096E-07	3.858E-07

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Table D.1 continued

		CH: Disposal, polypropylene, 15.9% water, to sanitary landfill	CH: disposal, plastics, mixture, 15.3% water, to sanitary landfill	CH: Disposal, refinery sludge, 89.5% water, to sanitary landfill
	Source:	Ecoinvent	Ecoinvent	Ecoinvent
	Output:	1 kg	1 kg	1 kg
Inventory Indicators				
Waste Disposal Provided [kg]		1.E+00	1.E+00	1.E+00
GaBi Inventory Metrics				
Net primary energy from renewable raw materials	MJ	4.567E-03	5.456E-03	1.314E-02
Gross primary energy from resources	MJ	3.237E-01	3.292E-01	3.792E-01
Net primary energy from resources	MJ	3.032E-01	3.086E-01	3.576E-01
Impact Indicators				
CML2001 - Dec. '07				
Acidification Potential	kg SO2-Eq.	7.164E-05	7.888E-05	1.279E-04
Eutrophication Potential	kg P-Eq.	1.561E-02	1.431E-02	1.226E-03
Freshwater Aquatic Ecotoxicity Potential	kg DCB-Eq.	9.129E-03	1.729E-03	1.914E-02
Global Warming Potential (100 years)	kg CO_2-Eq.	9.67E-02	8.956E-02	6.459E-01
Human Toxicity Potential	kg DCB-Eq.	6.018E-03	3.595E-03	5.64E-03
Marine Aquatic Ecotoxicity Potential	kg DCB-Eq.	1.182E+01	5.014E+00	1.776E+01
Ozone Layer Depletion Potential (steady state)	kg R11-Eq.	3.091E-09	3.101E-09	3.308E-09
Photochem. Ozone Creation Potential	kg Ethene-Eq.	2.976E-05	2.849E-05	1.36E-04
Terrestric Ecotoxicity Potential	kg DCB-Eq.	8.431E-05	9.554E-05	1.112E-03
TRACI 2002				
Ecotoxcity Air	kg 2,4-DCP-Eq	2.986E-04	3.252E-04	4.256E-04
Ecotoxcity Ground-Surface Soil	kg Benzene-Eq.	4.182E-05	4.5E-05	7.243E-05
Ecotoxcity Water	kg 2,4-DCP-Eq	1.21E+00	4.718E+00	3.31E+00
Eutrophication	kg N-Eq.	1.232E-02	1.297E-02	1.562E-03
Human Health Cancer Air	kg Benzene-Eq.	9.138E-06	9.799E-06	1.833E-05
Human Health Cancer Ground-Surface Soil	kg Benzene-Eq.	3.595E-07	3.603E-07	3.689E-07
Human Health Cancer Water	kg Benzene-Eq.	7.124E-03	1.53E-01	1.596E-01
Human Health Criteria Air-Point Source	kg PM2,5-Eq.	5.082E-05	5.165E-05	6.763E-05
Human Health Non Cancer Air	kg Toluene-Eq.	1.345E-02	1.419E-02	2.981E-02
Human Health Non Cancer Ground-Surface Soil	kg Toluene-Eq.	1.788E-03	1.846E-03	2.36E-03
Human Health Non Cancer Water	kg Toluene-Eq.	2.744E+02	5.084E+03	5.179E+03
Smog Air	kg NOx-Eq.	1.099E-07	1.105E-07	1.72E-07

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Table D.1 continued

		DE: Potable water from groundwater PE	DE: Organic waste water processing PE	RER: sodium hydroxide, 50% in H2O, production mix, at plant
	Source:	PE-GaBi	PE-GaBi	Ecoinvent
	Output:	1 kg	1 kg	1 kg
GaBi Inventory Metrics				
Net primary energy from renewable raw materials	MJ	6.01E-06	2.568E-03	9.568E-01
Gross primary energy from resources	MJ	8.022E-04	2.637E-01	2.509E+01
Net primary energy from resources	MJ	7.552E-04	2.428E-01	2.378E+01
Impact Indicators				
CML2001 - Dec. '07				
Acidification Potential	kg SO2-Eq.	8.327E-08	1.663E-04	5.45E-03
Eutrophication Potential	kg P-Eq.	8.59E-09	7.108E-05	4.174E-04
Freshwater Aquatic Ecotoxicity Potential	kg DCB-Eq.	2.466E-08	3.489E-04	8.438E-03
Global Warming Potential (100 years)	kg CO_2-Eq.	5.329E-05	7.655E-02	1.09E+00
Human Toxicity Potential	kg DCB-Eq.	1.303E-06	3.125E-03	3.844E-01
Marine Aquatic Ecotoxicity Potential	kg DCB-Eq.	2.63E-03	7.565E-01	6.175E+02
Ozone Layer Depletion Potential (steady state)	kg R11-Eq.	2.749E-12	5.62E-10	6.814E-08
Photochem. Ozone Creation Potential	kg Ethene-Eq.	9.64E-09	9.803E-06	3.628E-04
Terrestric Ecotoxicity Potential	kg DCB-Eq.	1.422E-08	1.507E-05	2.876E-02
TRACI 2002				
Ecotoxcity Air	kg 2,4-DCP-Eq	3.954E-08	4.922E-05	4.195E-02
Ecotoxcity Ground-Surface Soil	kg Benzene-Eq.	0.E+00	5.988E-07	2.5E-03
Ecotoxcity Water	kg 2,4-DCP-Eq	2.364E-07	1.356E-03	2.468E+00
Eutrophication	kg N-Eq.	5.159E-09	1.156E-04	4.269E-04
Human Health Cancer Air	kg Benzene-Eq.	4.673E-08	5.583E-06	2.468E-03
Human Health Cancer Ground-Surface Soil	kg Benzene-Eq.	0.E+00	1.867E-09	1.378E-05
Human Health Cancer Water	kg Benzene-Eq.	1.272E-09	2.742E-06	7.509E-04
Human Health Criteria Air-Point Source	kg PM2,5-Eq.	5.927E-07	7.247E-05	2.429E-03
Human Health Non Cancer Air	kg Toluene-Eq.	5.153E-05	2.424E-02	2.701E+00
Human Health Non Cancer Ground-Surface Soil	kg Toluene-Eq.	0.E+00	4.431E-05	9.208E-02
Human Health Non Cancer Water	kg Toluene-Eq.	3.918E-05	9.393E-02	1.384E+01
Smog Air	kg NOx-Eq.	5.623E-11	1.527E-07	2.04E-06

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Table D.1 continued

		RER: lubricating oil, at plant	Baling Wire, 10AWG
	Source:	**Ecoinvent**	**Ecoinvent**
	Output:	1 kg	1kg
Inventory Indicators			
Gross Feedstock Energy [MJ]		8.023E+01	6.31E+01
Net Feedstock Energy [MJ]		7.496E+01	5.989E+01
GaBi Inventory Metrics			
Net primary energy from renewable raw materials	MJ	3.25E-01	2.244E+00
Gross primary energy from resources	MJ	8.023E+01	6.31E+01
Net primary energy from resources	MJ	7.492E+01	5.983E+01
Impact Indicators			
CML2001 - Dec. '07			
Acidification Potential	kg SO2-Eq.	9.498E-03	6.032E-02
Eutrophication Potential	kg P-Eq.	2.564E-03	9.615E-03
Freshwater Aquatic Ecotoxicity Potential	kg DCB-Eq.	2.377E-02	3.96E-02
Global Warming Potential (100 years)	kg CO_2-Eq.	1.056E+00	3.4E+00
Human Toxicity Potential	kg DCB-Eq.	3.929E-01	5.931E+00
Marine Aquatic Ecotoxicity Potential	kg DCB-Eq.	3.394E+02	1.209E+03
Ozone Layer Depletion Potential (steady state)	kg R11-Eq.	6.484E-07	2.245E-07
Photochem. Ozone Creation Potential	kg Ethene-Eq.	4.848E-03	2.436E-03
Terrestric Ecotoxicity Potential	kg DCB-Eq.	1.062E-02	2.018E-01
TRACI 2002			
Ecotoxcity Air	kg 2,4-DCP-Eq	3.612E-02	2.039E+00
Ecotoxcity Ground-Surface Soil	kg Benzene-Eq.	1.985E-03	3.985E-03
Ecotoxcity Water	kg 2,4-DCP-Eq	8.931E-01	4.9E+00
Eutrophication Air	kg N-Eq.	2.31E-03	6.096E-03
Eutrophication Water	kg N-Eq.	1.912E-03	3.288E-02
Human Health Cancer Air	kg Benzene-Eq.	1.592E-04	1.881E-05
Human Health Cancer Ground-Surface Soil	kg Benzene-Eq.	3.89E-04	3.727E-03
Human Health Cancer Water	kg Benzene-Eq.	3.295E-03	1.932E-02
Human Health Criteria Air-Point Source	kg PM2,5-Eq.	2.362E+00	7.718E+01
Human Health Non Cancer Air	kg Toluene-Eq.	4.829E-01	1.207E-01
Human Health Non Cancer Ground-Surface Soil	kg Toluene-Eq.	8.142E+00	9.707E+01
Human Health Non Cancer Water	kg Toluene-Eq.	3.085E-06	9.655E-06
Smog Air	kg NOx-Eq.	3.25E-01	2.244E+00

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