Comparative Life-Cycle Assessment of Bottled Versus Tap Water Systems

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Contents

List of Tables

List of Figures

Abstract

This study uses life-cycle assessment (LCA) methodology to quantify life-cycle energy use, greenhouse gas emissions, solid waste generation and water use for delivering drinking water to consumer households in the United States. Three systems were considered in this analysis: 1) single-use disposable bottled water (500ml) sold in 24-packs, 2) Home and office delivery bottled water, 3) municipal tap water. For both the HOD and municipal tap systems, drinking water is served in a reusable drinking vessel (bottle or cup) that is periodically washed in a residential dishwasher. Variants of each system were constructed to represent a range of possible real-world scenarios using factors such as bottle type (virgin PET, rPET), water type (natural source, municipal source), distribution (regional, national, overseas), end-of-life treatment (landfill disposal, recycling), type of reusable drinking vessel (steel bottle, glass cup) and frequency of washing the reusable vessel.

With respect to life-cycle energy, solid waste, greenhouse gas emission and water use, the municipal tap systems outperform both HOD and single-use bottled systems. Single-use bottled systems consume 11-31 times more energy than tap systems. Production of plastic bottles is responsible for over 70% of the energy use of regional bottled systems, while with national and overseas distribution, transportation begins to dominate. Tap and HOD system energy use is dominated by residential washing of the reusable drinking vessel. Greenhouse gas emissions generally correlate with energy use. HOD systems consume 8-18% of energy relative to single-use systems, while municipal tap systems use 35-55% of HOD life-cycle energy. For solid waste, single-use systems perform the worst, followed by the HOD and municipal tap systems respectively. End-of-life treatment of bottles dictates single-use systems solid waste profile.

From an environmental perspective, municipal tap water is the preferred drinking water system.
Strategies to reduce the impact of bottled water may include bans at the organizational level (city governments, universities, and restaurants), education and outreach to encourage consumers to choose tap water and the expansion of state bottle bills to improve recovery of empty bottles. Results of this study can be used to inform consumers and legislators of the impacts of their choices with regard to drinking water.

Chapter 1

Introduction

1.1 Background

Water is essential for life. Human survival is dependent upon drinking water. In fact, estimates indicate that on average 60% of the human body is composed of water. Maintaining adequate hydration is necessary for proper functioning of nearly every bodily system *(Mayo Clinic)*. This includes the removal of toxins, regulation of body temperature, transport of nutrients and oxygen to cells, lubrication of joints and protection of organs and tissues. Daily activities deplete a human body's water reserves through breathing, perspiration and the excretion of waste. Dehydration leads to decreased human functioning often marked by headache and fatigue, though the health effects of prolonged dehydration can be much more severe including kidney failure and in extreme cases death. To avoid dehydration, we must replenish our water resources through the intake of food and fluids. Typically, 20% of one's daily water requirements are met through the consumption of food. The intake of fluids is necessary to make up the remaining 80%. As such, the provision of drinking water is of the utmost importance to society. Currently, the source of one's drinking water is a topic of much debate. Until recently, drinking water was primarily delivered by way of municipal distribution networks terminating in a household tap. With the explosion of the bottled water industry in the 1990's, however, consumers no longer have to rely on the municipal tap system to deliver their drinking water. Consequently, since 2003 more bottled water has been consumed by Americans than any other beverage category excepting carbonated soft drinks. In 2007, this translated to over 29 gallons per person *(Rodwan, 2008)*.

Much speculation has surrounded the tradeoffs involved in choosing between bottled and tap water. In a time of growing awareness of environmental issues including fossil resource depletion, emissions of greenhouse gases and rapidly filling landfills, there is a need to ensure that the systems we rely on to deliver basic needs, including the provision of drinking water, do so in an efficient manner and without undue toll on the environment. Faced with a choice between utilizing municipal tap systems or bottled water systems, an assessment of the environmental burdens of each serves to provide legislators and consumers with the information necessary to make informed decisions.

1.2 Rationale

The systems in place for delivering drinking water have considerable impact with regard to use of resources and release of pollution. In terms of energy resources, these systems are very intensive. Centralized water treatment and distribution systems consume more than 26 quads (quadrillion BTU) of commercial energy globally, or roughly 7% of total consumption *(James, Campbell, Godlove, 2002)*. These systems require considerable amounts of energy to collect water from surface and groundwater supplies, treat the influent to EPA mandated safety standards with both mechanical and chemical processes, and ultimately distribute to end users in households and businesses.

Bottled water has recently emerged as an alternative method of delivering drinking water. Convenient packaging and widespread availability have facilitated bottled water's emergence as a dominant beverage category, with sales second only to carbonated soft drinks as of 2003 *(Rodwan, 2008)*. As a system for delivering drinking water, bottled water also consumes considerable amounts of energy. The packages themselves, mostly bottles made of PET (polyethylene terephthalate) in various sizes, are derived from petroleum resources. The processes required for material production as well as container fabrication are energy intensive, while a finished bottle holds considerable embodied energy in its chemical bonds. In fact, the Pacific Institute estimates that in 2006, the equivalent of 17 million barrels of oil were consumed to produce the bottles used for American consumption of bottled water. Additional energy is consumed in the treatment of the water (varies by water source and method), the filling of containers in a bottling plant and the transportation of the filled bottled to retail outlets and ultimately homes and businesses. All told, the total amount of energy required to deliver a bottle of water to a consumer, depending on a variety of factors, can be as high as the equivalent of filling the bottle ¼ full with oil *(Pacific Institute, 2007)*. Further, after a single use, most empty bottles enter the waste stream. While well developed systems for recycling PET bottles exists in the U.S., recycling rates have been falling for a decade, and in 2006 only 23% of PET bottles sold were recycled *(NAPCOR, 2007)*. The remaining bottles end up in a landfill, amounting to roughly 4 billion pounds of bottles per year *(Kchao, 2008)*. In addition, estimates state that bottling water was responsible for more than 2.5 million tons of the greenhouse gas (GHG) CO_2 in 2006 *(Pacific Institute, 2007)*.

A recent increase in public awareness of the impacts of bottling water coupled with growing concern for the environment has elevated bottled water to the stage of public debate. The consumption of fossil resources required for manufacturing and transporting bottled water as well as the solid waste and emissions left in the wake has led to a backlash against bottled water. Articles drawing into question the growing consumption of bottled water and highlighting its impacts have appeared worldwide in reputable periodicals including the Wall Street Journal, New York Times, Los Angeles Times, Times (London) and the Daily Telegraph. Further, a critical mass of U.S. Mayors banning or restricting the purchase of bottled water with city funds (Los Angeles followed by San Francisco, Salt Lake City, Chicago, Seattle and most recently Toronto) led to the signing of Mayoral Resolution No. 90 in June 2007 at the annual meeting of the Conference of Mayors. The resolution entitled "The Importance of Municipal Water" directed an effort to compile information on the importance of municipal water and the impact of bottled water on the municipal solid waste stream *(Kchao, 2008)*. Aside from concerns regarding bottled water's impact on municipal waste streams, underlying this resolution is the notion that a major societal shift to bottled water could serve to undermine funding in municipal tap systems and potentially lead to equity issues for the poor.

The backlash against bottled water made its way into the restaurant world, with an increasing number of high-end restaurants in major cities such as San Francisco and New York no longer serving bottled water, opting instead to serve customers filtered municipal water in carafes *(Burros, 2007)*. More recently, this trend has begun to spread to universities. Washington University in St. Louis banned the sale of bottled water on its campus in January 2009, and claims to be the first university to do so *(Woznica, 2009)*. Their actions have not gone unnoticed as other universities have begun to move towards bans including the University of Pennsylvania, Brandeis University and Ohio Wesleyan. Further abroad, students at Leeds University in the United Kingdom recently voted to ban bottled water sales on campus in December 2008, a move covered extensively by the British newspaper, the Guardian, who expects many other U.K. schools to follow suit.

Clearly, the topic of bottled water is a divisive one. While sales appear to be down in 2008 *(Girard, 2009)*, the industry is well established and will likely see continued strong sales in the near term. Worldwide, the demand for drinking water will continue to rise with steadily growing population numbers. Priority should be given to meeting this demand with a wise and efficient use of resources. It is imperative, particularly today as we face threats from a changing global climate and shrinking stocks of energy resources, to evaluate systems for delivering drinking water in terms of energy resource consumption, environmental emissions and overall efficiency.

1.3 Thesis Statement

This study compares several contemporary systems for the delivery of drinking water to United States consumers, specifically municipal tap systems and bottled water systems. The analyses will use Life-Cycle Assessment (LCA) methodology to quantify burdens associated with the respective systems from a life-cycle perspective. The framework for the assessment will be based on parameters specific to the United States; the results, however, can be replicated using alternative parameters to derive broader implications.

While previous studies have addressed the impacts of drinking water delivery systems, these have been based entirely on conditions specific to Switzerland (energy, transportation systems etc.) *(Jungbluth, 2006)* or have failed to develop a comprehensive life-cycle energy estimate *(Gleick, Cooley, 2008)*. This study seeks to provide new insight by using systems specific to the U.S., including energy systems, transportation and municipal water and wastewater treatment. Further, to most accurately represent the life-cycle of a municipal tap water system, the life-cycle of a reusable vessel (bottle, cup) from which the water may be consumed, and the periodic washing of this vessel are modeled. Previous studies have not considered these two factors.

1.4 Literature Review

Few studies have been done comparing the environmental impact of systems for delivering drinking water. Jungbluth *(2006)* compared tap and bottled water variants in Switzerland using life-cycle approaches. The study found tap water results in less than 1% of the environmental impact of unrefrigerated bottled water. Further, while refrigerating and carbonating tap water increases the life-cycle impacts, doing so still only results in impacts 25% of those of bottled water. Jungbluth also reported that the origin of the water is more important than packaging, and that returnable bottles/jugs are only a reasonable alternative if the distance from the bottling facility to the consumer is relatively short.

Van Hoof, et al. *(2002)*, found substantially lower energy, solid waste and emissions resulting from consumption of tap water compared to bottled water. Filtered tap water shows impacts greater than those of unfiltered tap, but still outperforms bottled water.

Most recently, Gleick and Cooley *(2008)* quantified key energy inputs in bottled water required from production of bottles to point of use. They, however, did not use a comprehensive life-cycle model, citing variation in key processes, but rather calculated ranges in energy use. They found that for water transported short distances energy requirements are dominated by energy used to produce the bottles. Long-distance transport, however can lead to energy costs comparable to or even larger than those for producing the bottle.

Several studies have been conducted examining the environmental impacts of packaging systems. Keoleian, McDaniel and Spitzley *(1997)* evaluated nine packaging systems with respect to environmental performance, including LLDPE (linear low-density polyethylene) flexible pouches, paperboard gable top cartons, single-use and refillable glass bottles, single-use and refillable HDPE (high-density polyethylene) bottles, PC (polycarbonate) refillable bottles, steel cans and composite cans. They identified material production energy as the key factor influencing life-cycle energy and post-consumer waste contributing the majority of life-cycle solid waste.

Franklin Associates, a leading LCA consulting firm, has conducted numerous life-cycle based packaging studies. These include recently completed plastic packaging LCI studies for coffee and milk containers. The milk container study examined four half-gallon milk containers: a glass bottle, a PLA bottle, a HDPE bottle and a gable top paperboard carton. The study quantified energy use, solid waste generation and water and airborne emissions, and highlighted the tradeoffs and complexities of choosing the different packaging options (2008).

1.5 Overview of Life-Cycle Assessment

LCA is an environmental management tool used to describe and quantify the environmental burdens associated with a product or system throughout its entire life cycle (cradle-to-grave). The phases of a full product life-cycle include extraction of raw materials, material production, manufacturing, distribution, use and end-of-life. LCA involves the quantification of all energy and material inputs throughout each life-cycle phase as well as the resultant outputs (e.g. emissions, solid wastes). Further, potential environmental impacts associated with identified inputs and releases are assessed. LCA is often used to compare products or systems with the goal of determining the least burdensome option.

The procedures of an LCA are defined by the International Organization for Standardization (ISO) under the ISO 14000 environmental management standards. ISO 14040 concerns the principles and framework of LCA, while ISO 14044 establishes the requirements and guidelines for completing an ISO compliant LCA.

The ISO framework defines four required phases for an LCA. These include **1)** Goal and Scope Definition, **2)** Life Cycle Inventory (LCI), **3)** Life Cycle Impact Assessment (LCIA) and **4)** Interpretation.

1.5.1 Goal and Scope Definition

In the first step of an LCA, the goal and scope definition, the LCA practitioner defines the purpose of the study including the intended application and audience. Further, a function and "functional unit" of the product system is established. The "functional unit" serves as a means to provide a common reference for the inputs and outputs of the system. For example, the function of systems in this study is to provide drinking water to consumer households, and the functional unit is 1000 gallons of drinking water delivered to a consumer household. System boundaries, assumptions and limitations of the study are also set forth.

1.5.2 Life Cycle Inventory (LCI)

The life cycle inventory analysis involves the identification and quantification of all relevant inputs and outputs throughout the full life cycle of the given product system. This includes not only the direct material and energy inputs and environmental releases related to production and manufacturing but also those associated with upstream processes such as the energy required to extract raw fuels and materials from the earth. Conducting the LCI entails an accounting of the input and output flows associated with each process included in the system.

1.5.3 Impact Assessment

Using the results of the LCI, a life cycle impact assessment (LCIA) is conducted. The purpose of the LCIA, a technical, quantitative and/or qualitative process, is to characterize and assess the magnitude and significance of the potential environmental impacts LCI results. An LCIA consists of three steps:

- **Classification**: Data from the LCI is assigned to a number of selected impact categories (e.g. Greenhouse gases (GHG's) CO_2, CH_4 and N_2O are used to evaluate global warming impacts).
- **Characterization**: Modeling of the inventory result from each category in terms of a category indicator (e.g. conversion of emissions of all greenhouse gases to CO_2eq using global warming potentials for each gas).
- **Valuation**: Involves an integration of the results across impact categories using weight factors to facilitate a comparison between impact categories or allow for a single score

for the environmental performance of a product or system. This is considered an optional step.

1.5.4 Interpretation

The final step in LCA, the interpretation, serves to evaluate the results of the inventory analysis and impact assessment and recommend potential changes in the product system to improve environmental performance. The results are interpreted in relation to the goals of the study, significant results are highlighted and conclusions and recommendations are drawn.

1.6 Scope of Study

This research uses Life-Cycle Assessment (LCA) methodology to compare various scenarios for delivering drinking water to consumers in the United States. Three main systems, **(1)** single-serving disposable bottled water, **(2)** home and office delivery water (HOD) and **(3)** municipal tap water are analyzed to quantify energy use, greenhouse gas (GHG) emissions, generation of solid waste and water use. Variants of the 3 main systems were constructed based on packaging type, water source, distribution distance, type of reusable container and end-of-life treatment of packaging and containers.

1.6.1 Function and Functional Unit

The system **function** was the delivery of drinking water to consumers in the United States by way of several dominant delivery systems. The **functional unit** for the study was 1000 gallons of drinking water delivered to the consumer.

1.6.2 Model Overview and System Boundaries

Three baseline systems will be examined through a multitude of sub-scenarios. The three main systems encompass the delivery of 1000 gallons of drinking water via:

System 1: Single-use bottled water (500 ml bottles) sold in 24-packs. (7571 bottles/315.5 24-packs)

System 2: HOD water from 5-gallon jugs served in a reusable drinking container.

System 3: Municipal tap water served in a reusable drinking container.

For each of the systems, the following life-cycle stages are considered:

1) Cradle to material production for containers and secondary packaging.
2) Fabrication of containers (disposable and reusable) and secondary packaging.
3) Municipal treatment and pipeline distribution of tap water.

4) Operations at the bottling plant including water treatment and container filling.

5) Distribution of filled bottles/jugs.

6) Washing of reusable containers (single-serving and 5-gallon jugs).

7) Disposal/recycling of postconsumer materials (bottles, containers, secondary packaging).

In addition to the above, transportation between the various life-cycle stages was considered part of the system model. The transportation stages included in the analysis are:

1) Transportation of filled containers (bottled water) from bottling facility to distribution/retail center. This includes HOD water, which cycles between bottling facility and consumer household. Bottles were assumed to be fabricated on-site at bottling facility.

2) Transportation of bottled water from retail store to consumer household (round trip)

3) Transportation associated with end-of-life of containers, packaging (i.e. to landfill).

4) Transportation of reusable drink ware from manufacturing location to consumer household.

Several **key assumptions** were made in completing this study:

- Burdens related to capital goods were expected to be small relative to other processes and are not within the boundaries of the study. This includes production/maintenance burdens associated with manufacturing equipment, vehicles and water treatment equipment as well as construction of manufacturing, bottling and retail facilities and municipal water infrastructure.
- The production of pallets, likely used during various life-cycle stages, was not considered.
- The use of PE (polyethylene) stretch wrap to wrap pallets of bottled water was shown to represent less than 1% of the system, and was thus excluded from this study.
- The burdens associated with the shipment of secondary packaging from the supplier to the bottling facility were not considered.
- As is becoming increasingly the trend especially with larger bottlers, bottle/cap manufacturing was assumed to take place on-site at the bottling facility *(Senior, Dege, 2005)*.
- Labels, ink and glue associated with bottled water were assumed to be less than 1% of the system and were thus excluded from this study.

1.6.3 Data Categories

This section introduces the four data categories that were used to classify the results of the inventory analysis.

1.6.3.1 Energy Resources

Total primary energy consumed was tracked at each life cycle phase. This includes process related and feedstock energy. Feedstock energy accounts for the petroleum used as a raw material for making plastics.

1.6.3.2 Greenhouse Gas Emissions (CO_2 equivalents)

Greenhouse gas (GHG) emissions resulting were tracked through each life-cycle stage of the system and converted into CO_2 equivalents. This includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases generated from various processes.

1.6.3.3 Solid Waste

The mass of solid waste generated was tracked at each life cycle phase of the system. The solid waste category is an aggregation of solid waste generated from various processes and post-consumer waste that exit the system to enter a landfill. Materials that exit the system to be recycled for use in another product system do not accrue any of the burdens associated with disposal. This analysis did not account for credits (in material use or energy for example) for recycling material at the end-of-life; however a credit was given for the reduction in total solid waste.

1.6.3.4 Water Use

Water use, in gallons, was tracked through each life cycle stage for the system. This includes water used for various processes including material production, power generation (consumptive water use at the plant) and production of transport fuels as well as wastewater resulting from bottling and water treatment processes. Drinking water was not included in this category, as this was constant at 1000 gallons across all scenarios.

Chapter 2

Single-Use Bottled Water

2.1 System Description

This system encompasses the delivery of drinking water to consumers in 500 ml (16.9 oz) single-use bottles. Figure 2.1 shows the overview of the life cycle stages and processes modeled.

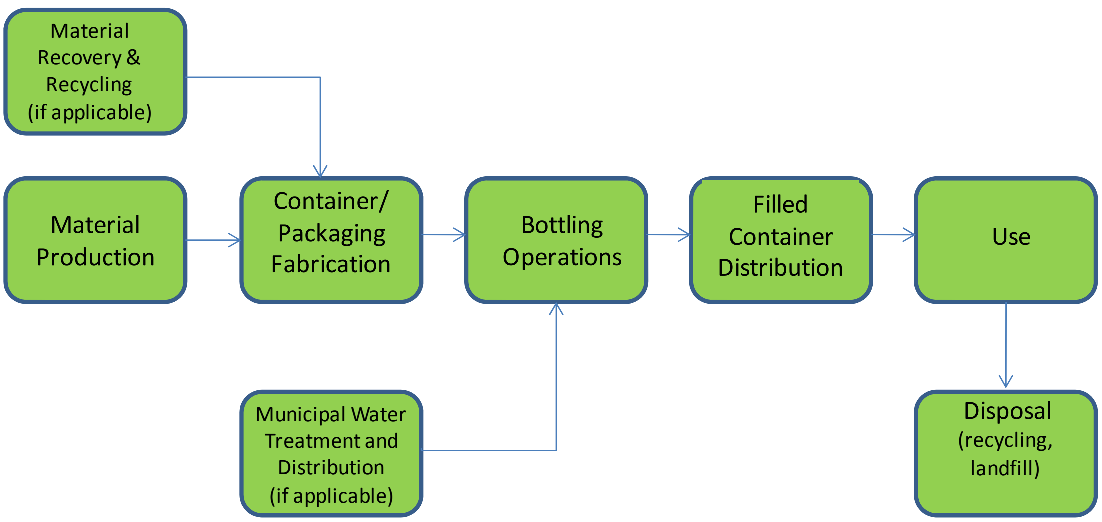

Figure 2.1: Overview of Life-Cycle System Model

This life cycle system begins with material production followed by the conversion of commodity/engineered materials by processes to produce bottles, caps and secondary packaging. At a bottling plant, 500 ml bottles are filled with drinking water (treated municipally or onsite at the bottling facility), capped and packaged into 24-packs. Complete multi-packs of bottled water are then transported by truck to a distribution center and onward (by various means and various distances) to a retailer in the United States. Multi-pack bottle water is then purchased by consumers and transported to the household via passenger vehicle. Bottled water is consumed, and the empty packaging (primary and secondary) is disposed of. The end-of-life fate of packaging materials varies by variant. The 1000 gallons of drinking water that makes up the functional unit requires 7571 bottles packaged into 315.5 24-packs.

2.1.1 Life Cycle Processes

Material Production:

During the Material Production Phase, raw materials are extracted from the earth and transformed into the desired finished materials. The Material Production Phase for this system represents the material production activities for primary (bottles, caps) and secondary packaging (corrugated boxes, polyethylene wrap). See **Appendix B** for details of material production processes.

Material Recovery and Recycling:

Some variants utilize 25% recycled PET as a material component for bottles. The Material Recovery and Recycling Phase represent the use of recycled PET in the fabrication of PET bottles for bottled water. In accordance with the recycling methodology set forth in **Appendix H,** material recovery and recycling activities in this case include the burdens of collecting and reprocessing the PET bottles for use in the fabrication of new PET bottles.

Container Fabrication:

During the container fabrication phase, finished materials including PET, PLA (polylactic acid) and PP (polypropylene) undergo fabrication processes that convert the materials into containers. See **Appendix B** for details on fabrication processes. It is assumed that container fabrication occurs on-site at a bottling facility.

Municipal Water Treatment:

The source of the drinking water for the bottled water systems differs by variant. For those variants that use municipal water for bottling, this phase encompasses the treatment of water at a municipal water treatment plant and subsequent distribution to a bottling facility. Data from the American Water Works Association (AWWA) was used to estimate average energy use at U.S water treatment plants. See **Appendix D** for details on the municipal treatment of drinking water.

Bottling Operations:

This phase represents operations at a bottling plant, including water treatment, container filling and packaging of individual bottles into 24-packs. The technologies employed for treating the water varies by the source of the water. In this study bottlers source their water from either municipal or natural (spring) supplies. Municipally sourced water will normally undergo microfiltration and reverse osmosis treatment (RO), followed by ozone treatment and UV (ultraviolet) disinfection. The treatment of water from natural sources, on the other hand, begins with micro-filtration followed by ozone treatment and UV disinfection. Naturally sourced water does not go through the RO process *(IBWA, 2009)*. See **Appendix E** for details on the bottling operations.

Filled Container Distribution:

This phase represents the distribution of filled 24-packs of bottled water, including:

(1) Travel from the bottling plant to a distribution facility
(2) Travel from the distributor to a retailer, and
(3) Travel from a retailer to a consumer household.

Distances and modes of travel are dependent on the variant under consideration. For example, a variant considers bottled water traveling to the U.S. from overseas via ocean freighter and subsequent ground transportation, while another considers bottled water produced regionally and transported by truck a relatively short distance. See **Appendix G** for details on transportation processes.

Use:

This phase represents the fate of bottled water once it arrives in a consumer household and prior to disposal; in other words, this is consumption of bottled water. No life-cycle processes are explicitly represented during this phase.

Disposal:

Disposal includes the end of life fate of primary containers (bottles) and secondary packaging. Primary containers are subject to alternative end of life scenarios (recycling, land filling) depending on the variant under consideration. Disposal of secondary packaging (corrugated board, PE wrap) is split between recycling and land fill based on the EPA estimates for municipal solid waste disposal in the US for various materials. Disposal burdens include those associated with transportation from consumer to final disposal and process related burdens of recycling and land fill disposal. See **Appendix H** for details regarding end of life processes.

2.2 Bottled Water System Variants for Analysis

Variants of the bottled water system were derived to represent the broad range of life-cycle impacts associated with the bottled water products available on the market today. The variants cover the possible spectrum between minimum and maximum impacts. Variants are intended to highlight some of the trade-offs and important parameters of the life-cycle of bottled water. Parameters used to construct variants include:

- **Primary Packaging (**bottle)**:** virgin PET; PET w/ 25% recycled content; PLA.
- **Water Source:** Spring (natural source); municipal supply.
- **Transportation distances:** Bottler to distributor; distributor to retailer; retailer to consumer household. (Note: as stated earlier, it is assumed that single-use bottles are blow molded on-site at the bottling facility)
- **Disposal:** landfill; recycle.

	1	**2**	**3**	**4**	**5**	**6**	**7**
Package:	PET - virgin	PET-25% recy. cnt.	PET-25% recy. cnt.	PLA	PET-25% recy. cnt.	PET-25% recy. cnt.	PET-virgin
Water Source:	Spring	Spring	Municipal	Spring	Spring	Spring	Spring
Travel:							
To distributor (mi):	100	100	100	100	1500	4900	6300
To retailer (mi):	20	20	20	20	20	20	20
To home (km):	8	8	8	8	8	8	8
Disposal:	Landfilled	Recycled	Recycled	Landfilled	Recycled	Recycled	Landfilled

Figure 2.2: Bottled Water System Variants

Variant 1: Regional distribution; virgin PET bottle; spring water; landfilled

Variant 1 represents regional sales of bottled water, such that the distribution network is limited to 100 miles of transport from the bottler to a distributor. Spring water is packaged in a virgin PET bottle (PET made from virgin material, rather than recycled material). Bottles are packaged into 24-multipacks using secondary packaging, and transported 100 miles to a distribution facility in a single-unit diesel truck. From a distributor, the bottled water is transported 20 miles to a retail location (grocery store, beverage vendor etc.) in single-unit diesel truck, before finally being purchased by a consumer and transported 4 km (8 km round trip) in a passenger vehicle (car) to the consumer household. 8 km is the average round-trip distance to a retail store in the U.S. *(Sivaraman, 2007)*. The bottled water is consumed and the empty container disposed of in a municipal landfill.

Variant 2: Regional distribution; rPET bottle (25%); spring water; recycled

Variant 2, also a regional model, introduces the use of recycled PET in the single-use bottle. Most recycled PET is down-cycled into other products (clothing, carpets and strapping) in an open-loop recycling system. Incorporating recycled PET (rPET) into bottles represents a closed-loop recycling system. Closed-loop recycling systems produce materials that have the same inherent properties as the original material and can thus displace the use of virgin material. In theory, a closed-loop recycling system can continue into perpetuity (though not in practice with current technology due to degradation of material). As such, closed loop systems are preferable to open-loop systems in which the material properties are not maintained. In the bottled water industry (if not the whole beverage industry), the use of rPET in the production of new bottles is an uncommon practice as of yet. Recently, however, Arkansas bottler Mountain Valley Spring Water has begun incorporating 25% rPET into all of its PET bottles. This variant uses 25% rPET as the baseline scenario. Sensitivities were conducted to determine the life-cycle benefits of using 50% and 100% rPET for the production of PET water bottles. See **Appendix I** for sensitivity analyses.

Variant 3: Regional distribution; rPET bottle; municipal water; recycled

Variant 3 is an equivalent scenario to variant 2 in all respects excepting the source of the water being bottled. This variant uses municipally sourced water, which has been subject to the municipal water treatment system prior to arriving at the bottling facility. Further, municipal water that is to be bottled undergoes reverse-osmosis treatment at the bottling plant, an energy intensive process. Reverse osmosis is not generally employed in the bottling of spring water. This variant is intended to highlight the differences in life-cycle impacts of spring versus municipally sourced bottled water.

Variant 4: Regional distribution; PLA bottle; spring water; landfilled

Variant 4 is equivalent to variant 1 in all respects excepting the material composition of the bottle. This variant uses a PLA bottle for the primary container. PLA is a biopolymer derived from renewable sources such as corn or sugar cane, rather than fossil based resources. While PLA is technically compostable, high-temperature commercial composting systems are required. At present, there is not a developed network of commercial facilities that are willing to accept PLA from municipalities. As a result, composting PLA is not a viable option for a consumer. PLA bottles entering the waste stream from this variant are consequently deposited in a landfill. This variant is intended to highlight the differences associated with producing PLA versus PET bottles.

Variant 5: National distribution; rPET bottle; spring water; recycled

Variant 5 represents the national sales of bottled spring water. This variant is comparable to bottled water systems employed by such national brands as Poland Spring. Spring water is bottled near the source (a natural source) and shipped long distances to penetrate the national market. Here, spring water is bottled into rPET containers, packaged into 24-multipacks and transported 1500 miles via tractor trailer diesel truck to a distribution center. From the distribution center, the bottled water is transported 20 miles to a retail center via single-unit diesel truck, purchased by a consumer and driven by passenger vehicle (car) 4 km (8 km roundtrip) to the household. Following consumption of the bottled water, the empty bottle is recycled.

Variant 6: International distribution; rPET bottle; spring water; recycled

Variant 6 represents an overseas bottled water system model, similar to the system employed by such international brands as Evian™. Spring water is bottled near the source and shipped via combination of rail, ocean freighter, and truck to reach an international market. Transportation modes and distance are based on inferences made from the Evian™ website. Spring water is bottled into rPET bottles in Évian-les-Bains, France, packaged into 24-multipacks and transported via rail to the Port of Marseilles, roughly 300 miles. From the Port of Marseilles, the bottled water is shipped across the Atlantic Ocean via ocean freighter to the Port of New York, NY, roughly 4500 miles before continuing on to a distribution center via single-unit diesel truck an additional 100 miles. From the distribution center, the bottled water is transported 20 miles via single-unit diesel truck to a retail store before finally being purchased and transported 4 km (8 km round trip) to a consumer household in a passenger vehicle. Following consumption of the bottled water, the empty bottles are recycled.

Variant 7: Extended international distribution; virgin PET bottle; spring water; landfilled

Variant 7 is an additional overseas bottled water system, and represents spring water which is packaged into virgin-PET bottles, and transported to the Port of New York, NY (same transportation modes and distances, 300/4500 miles). From port, however, the bottled water is trucked an additional 1500 miles to a distribution center in the central United States. From the distribution center, the bottled water is trucked 20 miles to a retailer, purchased and transported 4 km (8 km roundtrip) in a passenger vehicle. Empty bottles are disposed of in a landfill.

2.3 Results

Using SimaPro 7 LCA software and Microsoft Excel, the life-cycle impacts of Single-Use Bottled Water variants were evaluated. Results were evaluated for 1000 gallons of drinking water (7571 PET bottles/315.5 24-packs) and are presented in **Table 2.1** below by variant, as defined in *section 2.2.*

Table 2.1: Combined Results By Variant

Single-Use Bottled Water (1000 gallons)

[1000 gallons = 3785.4 liters]	Variant						
	1	2	3	4	5	6	7
Energy (MJ)							
Container Production	13857.2	11940.8	11940.8	12449.2	11940.8	11940.8	13857.2
2° Pkng Production	1582.3	1582.3	1582.3	1582.3	1582.3	1582.3	1582.3
Bottling	687.6	687.6	941.9	687.6	687.6	687.6	687.6
Distribution	2202.5	2202.5	2202.5	2202.5	10132.8	9119.7	17050.0
Consumer Transport	245.5	245.5	245.5	245.5	245.5	245.5	245.5
End-of-Life (ctrs, pkng.)	26.6	2.3	2.3	26.6	2.3	2.3	26.6
Total:	**18601.7**	**16661.0**	**16915.3**	**17193.8**	**24591.3**	**23578.2**	**33449.2**
Solid Waste (kg)							
Container Production	13.0	21.5	21.5	7.8	21.5	21.5	13.0
2° Pkng Production	7.7	7.7	7.7	7.7	7.7	7.7	7.7
Bottling operations:	6.8	6.8	9.1	6.8	6.8	6.8	6.8
Distribution:	0.8	0.8	0.8	0.8	3.8	3.5	6.5
Consumer Transport	0.001	0.001	0.001	0.001	0.001	0.001	0.001
End-of-Life (ctrs, pkng.)	169.5	51.4	51.4	169.5	51.4	51.4	169.5
Total:	**197.9**	**88.3**	**90.6**	**192.6**	**91.3**	**90.9**	**203.5**
GWP (kg CO_2 eq)							
Container Production	571.8	506.9	506.9	152.5	506.9	506.9	571.8
2° Pkng Production	108.1	108.1	108.1	108.1	108.1	108.1	108.1
Bottling operations:	40.2	40.2	56.1	40.2	40.2	40.2	40.2
Distribution:	159.6	159.6	159.6	159.6	737.1	671.3	1248.8
Consumer Transport	19.1	19.1	19.1	19.1	19.1	19.1	19.1
End-of-Life (ctrs, pkng.)	26.8	2.8	2.8	26.8	2.8	2.8	26.8
Total:	**925.7**	**836.7**	**852.6**	**506.3**	**1414.2**	**1348.4**	**2014.8**
Water Use (gallons):							
Ctr/Pkng Production:	175.0	175.0	175.0	175.0	175.0	175.0	175.0
Bottling:	67.2	67.2	400.5	67.2	67.2	67.2	67.2
Power Production	701.0	690.0	716.2	701.0	690.0	690.0	701.0
Transportation	11.1	11.1	11.1	11.1	32.7	11.1	36.1
Total:	**954.3**	**943.3**	**1302.8**	**954.3**	**965.0**	**943.4**	**979.4**

2.3.1 Life-Cycle Energy:

Figure 2.3 displays life-cycle energy results by variant which range from **16,661 MJ** to **33,449 MJ**:

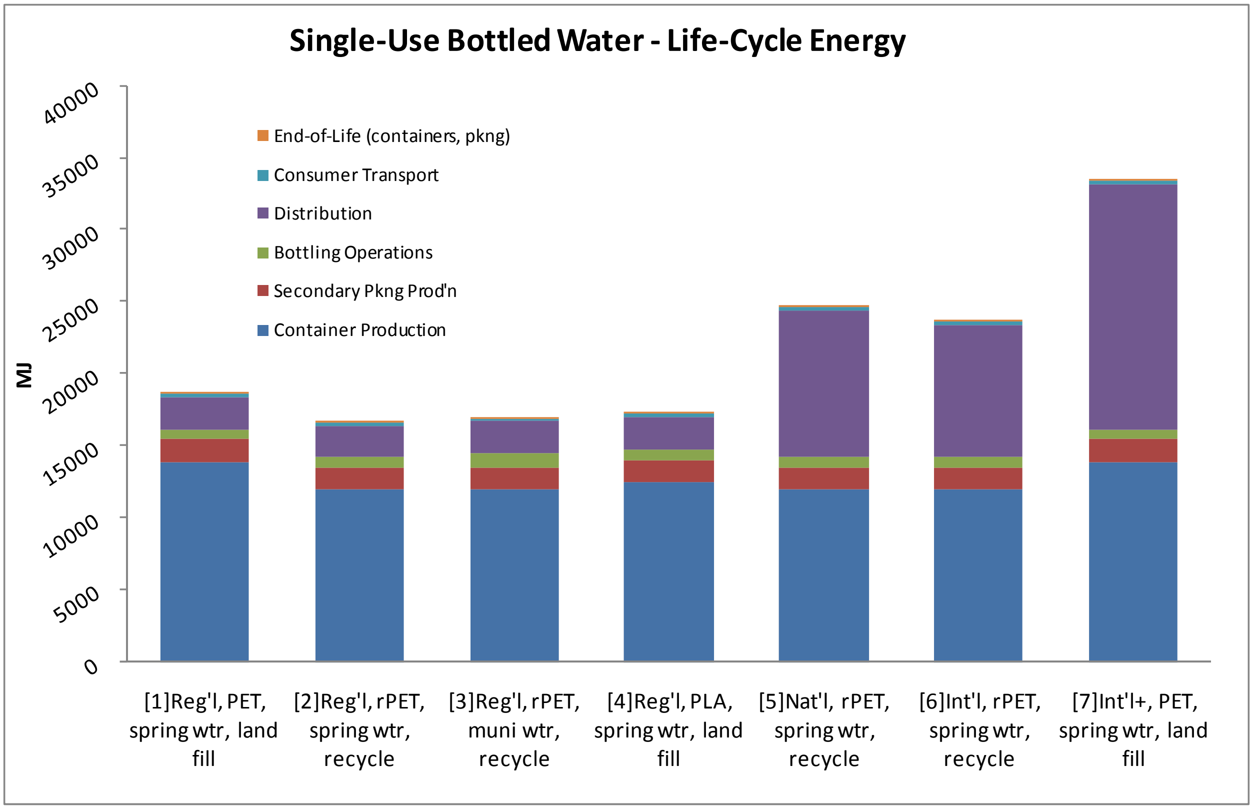

Figure 2.3: Life-Cycle Energy by Variant

Variant 1: Regional distribution; virgin PET bottle; spring water; landfilled

Life-cycle energy consumption is dominated by the container production (material production and fabrication of virgin-PET bottle and PP cap). At **13,857.2 MJ**, container production represents nearly 75% of the life-cycle energy of Variant 1. Despite a regional distribution model, distribution is the second largest contributor to life-cycle energy, followed by the production of the secondary packaging. Bottling, consumer transport and end-of-life (collection and transportation of waste to a landfill) collectively represent roughly 5% of the life-cycle energy.

Variant 2: Regional distribution; rPET bottle (25%); spring water; recycled

Life-cycle energy consumption is dominated by the container production (material production and fabrication of virgin-PET bottle and PP cap). At **11,940.8 MJ**, container production represents nearly 72% of the life-cycle energy of Variant 2. The decrease in container production energy from **Variant 1** is attributed to the use of 25% rPET in the bottle. Producing bottles from recycled PET is less energy intensive than doing so from virgin material. Despite a regional distribution model, distribution is the second largest contributor to life-cycle energy, followed by the production of the secondary packaging. Bottling, consumer transport and end-of-life (collection and transportation of waste to a landfill) collectively represent less than 6% of the life-cycle energy.

Variant 3: Regional distribution; rPET bottle; municipal water; recycled

The life-cycle energy profile of Variant 3 is identical to that of Variant 2 with one exception. The use of municipal water for bottling leads to an increase in bottling energy (941.9 MJ vs. 687.6 MJ). Bottling municipal water is more energy intensive than bottling spring water for two reasons. First, the municipal water has already undergone treatment at a municipal water treatment facility, a process that consumes energy. Further, industry standard is to further treat municipal water to be bottled with reverse osmosis, an energy intensive process, while spring water will not undergo this additional treatment step. Here bottling energy increases to 6% of life-cycle energy (from 4.1%).

Variant 4: Regional distribution; PLA bottle; spring water; landfilled

Relative to virgin-PET (variant 1), the PLA container production process exhibits decrease in container production energy (12,499.2 MJ vs. 13,857.2 MJ). PLA, a biopolymer, is derived from renewable resources rather than fossil based resources, and as a consequence is less intensive to produce. Energy use in all other life-cycle stages remains unchanged from Variant 1.

Variant 5: National distribution; rPET bottle; spring water; recycled

While life-cycle energy is still dominated by container production (49%), national distribution translates to more than a 4-fold increase in distribution energy use (2,205.5 MJ to 10,132.8 MJ). Here, distribution accounts for 41% of life-cycle energy. Energy use at other life-cycle stages remains unchanged from Variant 2.

Variant 6: International distribution; rPET bottle; spring water; recycled

Life-cycle energy continues to be dominated by container production (51%), however, overseas distribution translates to more than a fourfold increase in distribution energy use (2,205.5 MJ to 9,119.7 MJ) relative to the regional variants. Here, distribution accounts for 39% of life-cycle energy. Energy use at other life-cycle stages remains unchanged from other spring water variants. It is interesting to note that while distribution distance increased drastically from the national distribution model (variant 5), distribution energy has actually decreased from 10,132.5 MJ to 9,119.7 MJ. This is a product of the relative efficiency of ocean freight transport (which accounts for 4,500 of the 4,900 miles of the overseas distribution model) versus the tractor-trailer transport of the national distribution model.

Variant 7: Extended international distribution; virgin PET bottle; spring water; landfilled

Here, life-cycle energy is dominated by distribution energy use (**51%** of life-cycle energy). The distribution model for Variant 7 results in a nearly eightfold increase in distribution energy from regional variants (from 2,205.5 MJ to 17,050 MJ). This variant employs the use of virgin-PET bottles and hence exhibits an increase in container production energy use from Variant 6. Here we see the highest life-cycle energy of the bottled variants.

2.3.2 Life-Cycle Solid Waste

Figure 2.4 displays life-cycle solid waste results by variant which ranges from **88.3 kg** to **203.5 kg**:

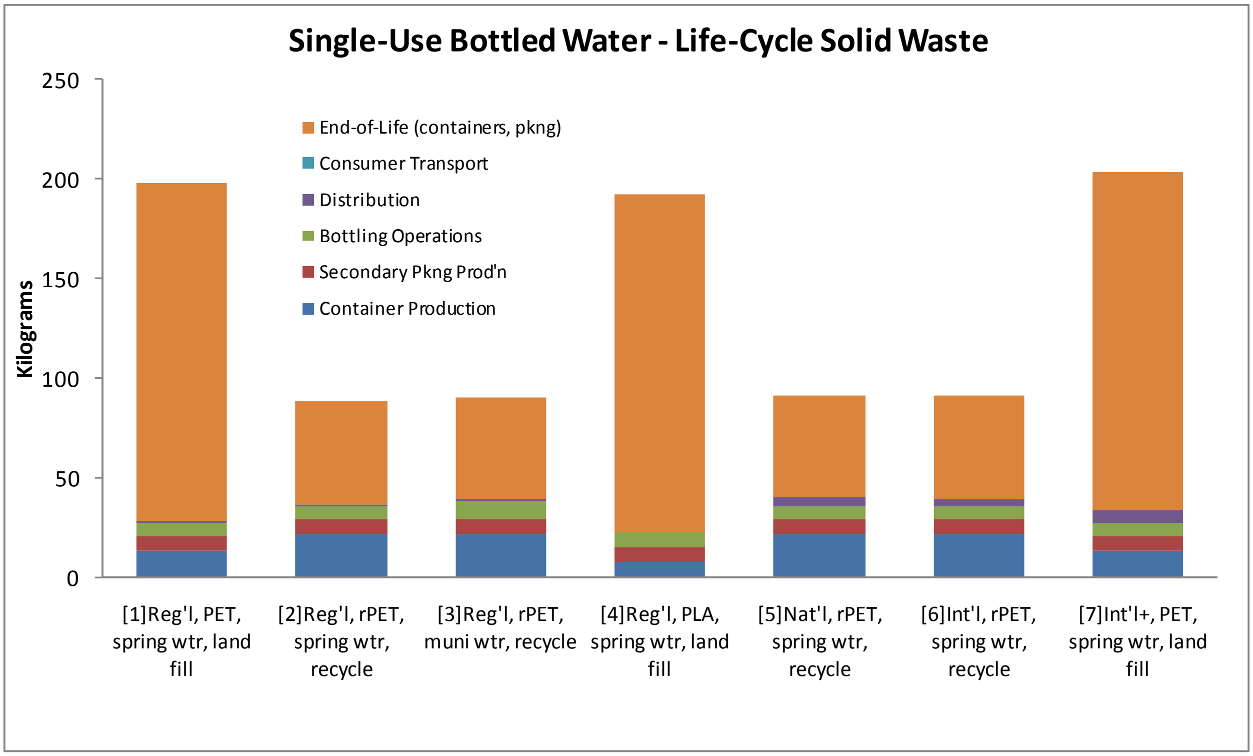

Figure 2.4: Life-Cycle Solid Waste by Variant

Variant 1: Regional distribution; virgin PET bottle; spring water; landfilled

Life-cycle solid waste is dominated by the end-of-life of containers and secondary packaging – the materials that end up being deposited in a landfill. The 169.5 kg of post-consumer solid waste generated by this variant (PET, PP, PE, corrugated cardboard) accounts for more than 85% of life-cycle solid waste. Process related solid wastes from the production of containers and secondary packaging as well as bottling operations account for roughly 14% while those associated with distribution and consumer transport are negligible.

Variant 2: Regional distribution; rPET bottle (25%); spring water; recycled

Life-cycle solid waste is dominated by land filling of the polypropylene bottle caps and secondary packaging, including the cardboard tray and polyethylene wrap associated with 24-packs of bottled water. This variant employs recycling of PET, and thus the bottles are diverted from the solid waste stream. This accounts for the decrease from in solid waste **Variant 1** associated with the end-of-life of containers and packaging. The 51.39 kg of post-consumer solid waste (PP, PE, corrugated cardboard) accounts for more than 58% of life-cycle solid waste. Process related solid wastes from the production of containers and secondary packaging as well as bottling operations account for roughly 33% while those associated with distribution and consumer transport are negligible. Relative to Variant 1, solid waste resulting from container production has increased from 13.04 kg to 21.54 kg. Process related solid wastes are greater for producing rPET bottles than virgin-PET. Overall, Variant 2 shows a 56% reduction of total solid waste resulting from the recycling of PET bottles after their useful life.

Variant 3: Regional distribution; rPET bottle; municipal water; recycled

Like energy use, life-cycle solid waste remains unchanged from Variant 2, excepting that associated with bottling. Here the use of municipal water for bottling and the associated increase in energy use leads to the generation of more process related solid waste. Variant 3 shows an increase in bottling solid waste to 10% of life-cycle solid waste (from 7.7%).

Variant 4: Regional distribution; PLA bottle; spring water; landfilled

Life-cycle solid waste is dominated by the end-of-life of containers and packaging. The end-of-life stage represents 88% of life-cycle solid waste. While technically biodegradable, PLA requires the high heat and pressure of industrial composting facilities to decompose. Few facilities exist nationwide for the composting of PLA. For this study, it was assumed that PLA is sent to a land fill. The PLA bottle performs best (relative to virgin-PET and rPET) with regards to solid waste from the container production process (4% of life-cycle solid waste).

Variant 5: National distribution; rPET bottle; spring water; recycled

Life-cycle solid waste is dominated by land filling of the polypropylene bottle caps and secondary packaging, including the cardboard tray and polyethylene wrap associated with 24-packs of bottled water. This variant employs recycling of PET, and thus the bottles are diverted from the solid waste stream. The increases in distribution energy results in a commensurate increase in process related solid waste associated with distribution. Here distribution solid waste accounts for 4% of life-cycle solid waste and more than a fourfold increase from the regional distribution variants.

Variant 6: International distribution; rPET bottle; spring water; recycled

Life-cycle solid waste is dominated by land filling of the polypropylene bottle caps and secondary packaging, including the cardboard tray and polyethylene wrap associated with 24-packs of bottled water. The increases in distribution energy results in a commensurate increase in process related solid waste associated with distribution. Here distribution solid waste accounts for 3.8% of life-cycle solid waste and more than a fourfold increase from the regional distribution variants. Due to the relative efficiency of ocean freight versus tractor-trailer transport, despite a drastic increase in distribution distance from the national distribution model, we see a decrease in solid waste related to distribution (3.45 kg versus 3.85 kg).

Variant 7: Extended international distribution; virgin PET bottle; spring water; landfilled

Variant 7 generates the most solid waste of any of the bottled variants. This is a result in increase in solid waste from the extended overseas distribution, the use of virgin-PET and the land filling of bottles. Due to the land filling of bottles, end-of-life represents 83% of life-cycle solid waste. The extended overseas distribution model causes distribution related solid waste to increase from **3.45** to **6.46 kg**, a nearly twofold increase.

2.3.3 Life-Cycle Greenhouse Gas Emissions

Figure 2.5 displays life-cycle GHG results by variant which ranges from **506 kg CO_2eq** to **2,015 kg CO_2eq**:

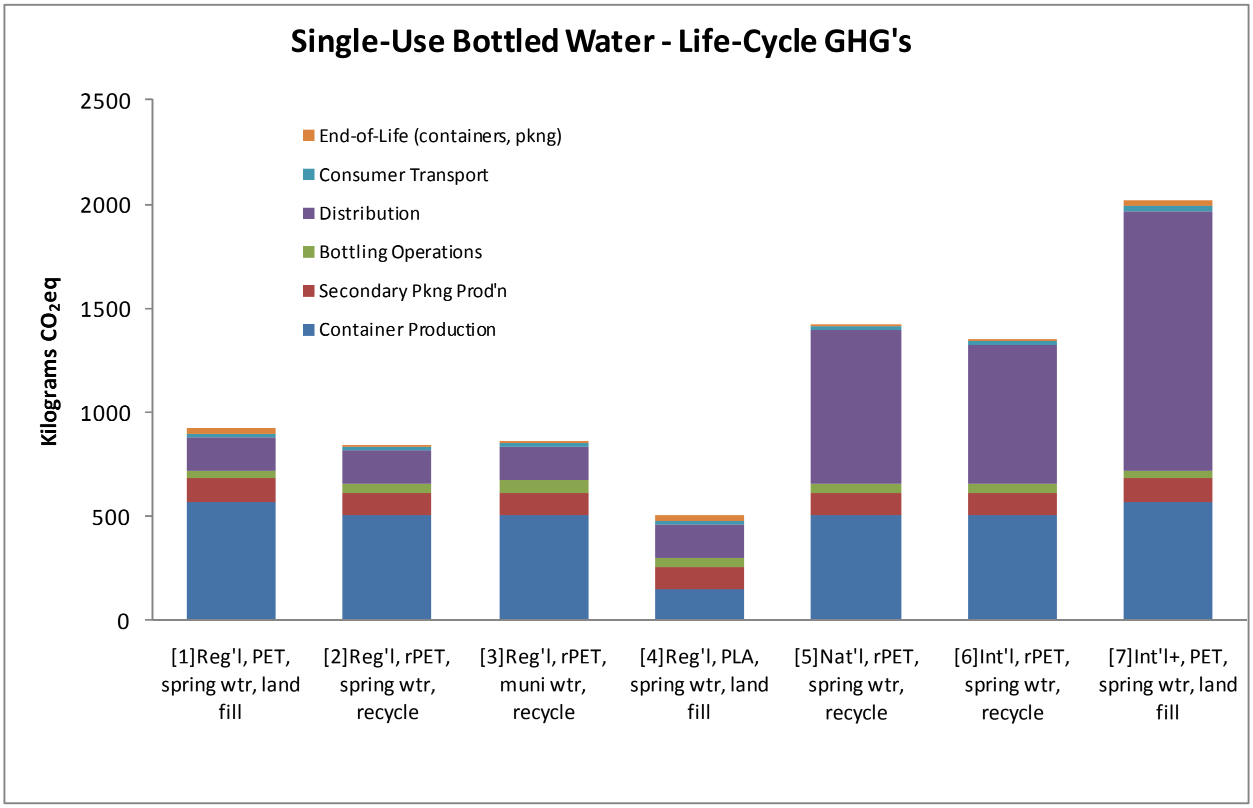

Figure 2.5: Life-Cycle Greenhouse Gas Emissions by Variant

Variant 1: Regional distribution; virgin PET bottle; spring water; landfilled

Typically, greenhouse gas emissions correlate with energy use. As such, life-cycle GHG emissions share the same top three contributors with life-cycle energy: container production, distribution and secondary packaging production. These three represent 62%, 17% and 12% of GHG emissions respectively. The remainder, bottling, consumer transport and end-of-life, collectively account for less than 10% of life-cycle GHG emissions.

Variant 2: Regional distribution; rPET bottle (25%); spring water; recycled

Life-cycle GHG emissions share the same top three contributors with life-cycle energy: container production, distribution and secondary packaging production. These three represent 61%, 20% and 13% of GHG emissions respectively. The remainder, bottling, consumer transport and end-of-life, collectively account for roughly 7% of life-cycle GHG emissions. Overall, we see a 10% reduction of total GHG emissions due to a reduced volume of solid waste collected and transported to a land fill.

Variant 3: Regional distribution; rPET bottle; municipal water; recycled

Life-cycle greenhouse gas emissions increase slightly from Variant 2 due to the increased energy demands of bottling municipal water. Greenhouse gases emitted during the bottling process account for 7% of life-cycle emissions (up from 5% with Variant 2).

Variant 4: Regional distribution; PLA bottle; spring water; landfilled

Life-cycle GHG emissions are dominated by distribution related emissions, at 32% of life-cycle emissions. Relative to Variant 1, we see a drastic reduction in the emissions from container production as they fell from 62% of life-cycle emissions to 30%. While production of PLA is significantly less intensive then PET (virgin or rPET) with respect to GHG emissions, much of the reduction can be attributed to plant specific bonuses from special energy certificates. The data used in this study for production of PLA are specific to the Natureworks Plant in Nebraska, the largest PLA plant in the world, and reflects carbon dioxide emissions offsets through wind power certificates specific to the plant.

Variant 5: National distribution; rPET bottle; spring water; recycled

At 52%, distribution related GHG emissions dominate the life-cycle here. The **737.07 kg of CO_2eg** associated with distribution is more than a fourfold increase from the regional variants. Emissions from all other life-cycle stage remain unchanged from Variant 2.

Variant 6: International distribution; rPET bottle; spring water; recycled

At 50%, distribution related GHG emissions dominate the life-cycle here. The **671.33 kg CO_2eg** associated with distribution is more than a fourfold increase from the regional variants. Emissions from all other life-cycle stage remain unchanged from Variant 5. Due to the relative efficiency of ocean freight versus tractor-trailer transport, despite a drastic increase in distribution distance from the national distribution model, we see a decrease in GHG emissions related to distribution (671.33 versus 737.07 kg CO_2eg).

Variant 7: Extended international distribution; virgin PET bottle; spring water; landfilled

At 62%, distribution related GHG emissions dominate the life-cycle here. The **1248.79 kg CO_2eg** associated with distribution is more than an eightfold increase from the regional variants, and nearly a twofold increase from the overseas distribution model employed by Variant 6. This variant employs the use of virgin-PET bottles and hence exhibits an increase in container production GHG emissions from Variant 6. Here we see the highest life-cycle GHG emissions of the bottled variants.

2.3.4 Life-Cycle Water Use Results

Figure 2.6 displays life-cycle water use results by variant which ranges from **943 gallons** to **1303 gallons**:

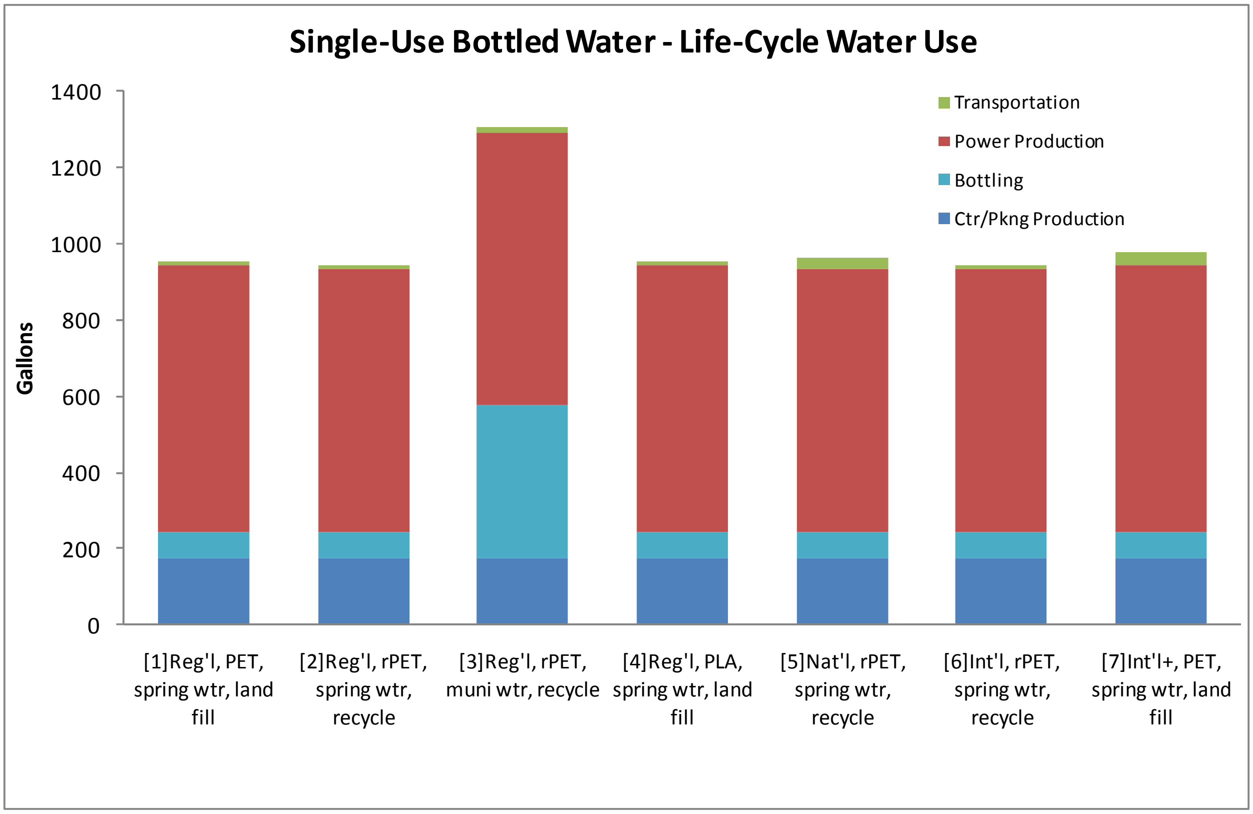

Figure 2.6: Life-Cycle Water Use by Variant

Variant 1: Regional distribution; virgin PET bottle; spring water; landfilled

Life-cycle water use for Variant 1 is dominated (73%) by water used during power production activities, followed by material production for packaging and containers (PET, PP, corrugated board, LDPE) Water use associated with bottling is a product of rinsing bottles prior to filling.

Variant 2: Regional distribution; rPET bottle (25%); spring water; recycled

Life-cycle water is slightly reduced from Variant 1. The reduction in water used for power production is due to the lower energy requirements associated with the rPET bottle (relative to virgin bottles).

Variant 3: Regional distribution; rPET bottle; municipal water; recycled

This variant has the highest total water use of among all variants. Water use increases dramatically with the bottling of municipal water. Bottlers typically treat municipal water with reverse osmosis, something that is not done with spring water. Reverse osmosis produces 25% wastewater. As such, to produce 1000 gallons of drinking water from reverse osmosis, 1333.3 gallons of influent is required, and 333.3 gallons exit the process as wastewater. Variant 3 bottling water use increases to 400.5 gallons, and shows a 38% increase in total water use from Variant 2.

Variant 4:

Water use is unchanged from Variant 1.

Variant 5:

Variant 5 transportation related water use increases 196% from the regional variants (1-4) due to national distribution of bottled water.

Variant 6:

Despite the overseas distribution model used for Variant 6, we see a reduction in transportation related water use. This is due to the relative efficiency of ocean freighter travel versus tractor-trailer travel.

Variant 7:

The extended overseas distribution model of Variant 7 requires additional transportation related water use. Transportation water use increases 225%.

2.4 Discussion

As evidenced from the analysis of bottled water variants, several key factors determine the life-cycle impacts of a single-use bottled water system: the material composition of the single-use bottle, the end-of-life treatment of those bottles and the details of distribution including mode and distance.

The material composition of the primary container (500 ml bottle) is a significant contributor to the life-cycle energy and greenhouse gas profile of single-use bottled water. For regionally distributed bottled water packaged in virgin-PET, container production (material production and container fabrication) constitutes 75% of life-cycle energy. The use of rPET (25% recycled content) reduces container production energy by 14% (13,857.2 to 11,940.8 MJ), and life-cycle energy by 10%. Similar reductions are seen in greenhouse gas emissions with rPET reducing container production GHG's by 11% (571.83 to 506.89 kg CO_2eq), and life-cycle GHG's by 10%. The use of a PLA bottle also reduces life-cycle energy and greenhouse gas emissions to the system. Relative to the virgin scenario, PLA bottles reduce container production energy by 10% (13,857.2 to 12,449.2 MJ) and life-cycle energy by 8%. More dramatic reductions are seen in greenhouse gas emissions. The use of PLA reduces container production emissions by 73% (571.83 to 152.49 kg CO_2eq) and life-cycle emissions by 45%. It should be noted that the majority of the GHG reduction from the use of PLA are specific to the Natureworks Plant in Nebraska, the largest PLA plant in the world. The PLA data used in this study are specific to this plant and reflect carbon dioxide emissions offsets through wind power certificates specific to the plant. There is some potential that PLA could generate methane when landfilled. Unfortunately, few studies have been published that address the greenhouse gas emissions associated with land filling biodegradable polymers. Some research suggest that PLA does not degrade in a well-engineered landfill where there is little moisture or warmth (Bohlmann, 2004). While more research is needed to understand the fate of degradable plastics in a landfill, this study assumes no biodegradation of PLA nor associated emissions.

The end-of-life treatment of the single-use bottles has a considerable impact on the life-cycle solid waste for the single-use bottled systems. End-of-life, the post-consumer portion of solid waste (bottles, caps, secondary packaging), is the dominant solid waste category across all variants and ranges from 56-86% of life-cycle solid waste. By diverting bottles from a land fill through recycling, end-of-life solid waste is reduced by 70%, from 169.5 kg to 51.39 kg. The remaining 51.39 kg of post-consumer solid that is sent to a landfill is made up of the polypropylene caps and secondary packaging (polyethylene wrap and corrugated board).

Distribution can be a major contributor to life-cycle impacts of single-use bottled water. Distribution ranges from 12-51% of life-cycle energy across the variants depending on the distribution pattern in place. Shifting from a regional to national distribution pattern increases distribution energy 360% (2,202.5 MJ to 10,132.8 MJ) as distribution energy rises from 12% to 41% of life-cycle energy. Overseas distribution increases distribution energy 314%, notably less than national distribution despite much greater travel distance. This is a function of the relative efficiency of ocean freighter versus tractor-trailer travel. The extended overseas model increases distribution energy 674%, from 2,202.5 to 17,050 MJ. Under this scenario, distribution energy accounts for 51% of life-cycle energy and becomes the dominant contributor to life-cycle energy, replacing container production.

Chapter 3

Home and Office Delivery (HOD) Bottled Water

3.1 System Description

This system represents the delivery of drinking water to consumers in 5-gallon jugs through a home and office delivery (HOD) provider. At the household, the drinking water is consumed through the use of a reusable drinking vessel (stainless steel bottle, glass cup). Figure 3.1 shows the overview of the system model.

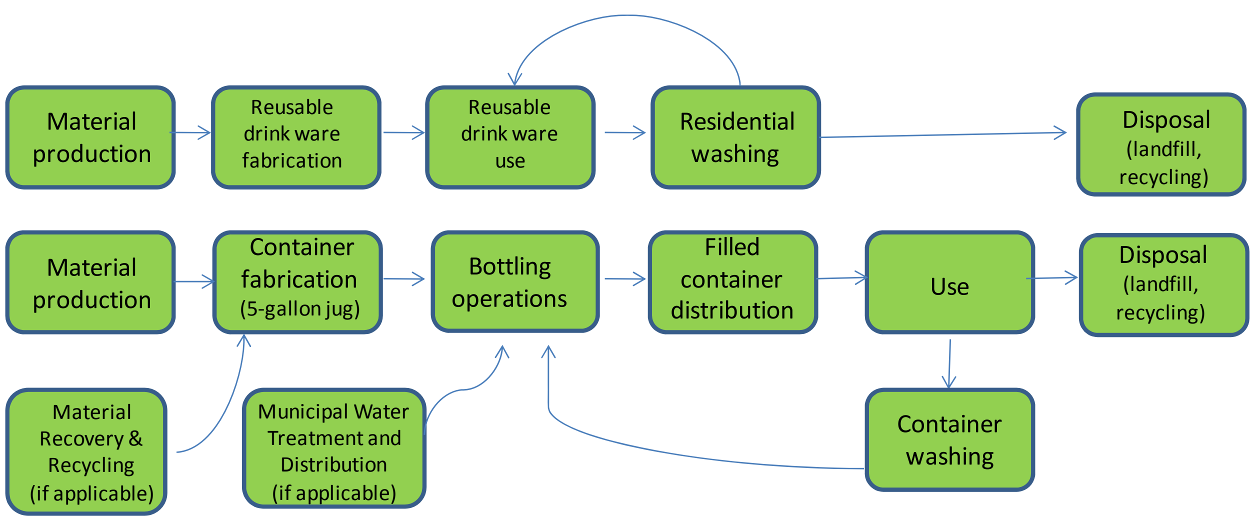

Figure 3.1: Overview of Life-Cycle System Model

This life cycle begins with material production, including those required for the production of the 5-gallon jug (PET, PC) the reusable drinking vessel (stainless steel bottle, glass cup). This system does not involve the use of secondary packaging. While it is possible that some type of secondary packaging is used during the life-cycle of HOD water, no data was found concerning this, and as such secondary packaging was not included in the analysis. Finished materials undergo fabrication processes to produce the reusable drink ware (stainless steel bottle, glass cup) and the water bottle (5-gallon jug). At a bottling plant, 5-gallon jugs are filled with drinking water (treated municipally and/or on-site at the bottling facility). Filled containers are then delivered to a consumer household as part of a home and office delivery system. The drinking water is served in a reusable container which is periodically washed in a residential dishwasher. Empty 5-gallon jugs are collected by fillers, returned to the bottling plant, washed and subsequently reenter the HOD system. The end-of-life fate of the 5-gallon jug varies by scenario, while the reusable container is recycled. The number of times a 5-gallon jug can be reused determines the number of jugs that need to be fabricated to deliver the functional unit of 1000 gallons of drinking water. Reuse can vary considerably (25-100 times) depending on many factors including climate and handling, but most importantly material composition *(Davis, 2008)*. Polycarbonate is a stronger, more durable material than PET, and as a result has a longer life *(Hamilton, 2001)*. For this analysis, 50 reuses per jug were assumed for PC jugs, while only 25 for PET. This translates to the manufacture of 4 PC jugs or 8 PET jugs to deliver 1000 gallons of drinking water.

The baseline scenario analyzes the use of two reusable drinking vessels (stainless steel bottle, glass cup) to consume the whole functional unit (1000 gallons of drinking water). Sensitivities are run to determine the life cycle impacts of shorter container life requiring the use of additional containers. See **Appendix I** for sensitivity analysis regarding container life and the use of additional reusable containers. The stainless steel bottle is manufactured in China and brought to the consumer by a combination of ocean freight and truck transport. For the glass cup, distribution distance was assumed to be 300 miles by truck. While paper cups are often used to consume HOD water in an office setting, this study examines the consumption of HOD water in a consumer household setting.

3.1.1 Life Cycle Processes

Material Production:

During the material production phase, raw materials are extracted from the earth and transformed into the desired finished materials. The material production phase for this system represents the material production activities for water bottles (5-gallon jugs) and reusable drinking vessels (steel bottle, glass cup). See **Appendix B** for details of material production processes.

Material Recovery and Recycling:

Some variants utilize 25% recycled PET as a material component for the 5-gallon jug. The Material Recovery and Recycling phase represents the use of rPET in the fabrication of PET bottles (5-gallon jugs) for bottled water. In accordance with the recycling methodology set forth in **Appendix H**, material recovery and recycling activities in this case include the burdens of collecting and reprocessing the 5-gallon PET jugs for use in the fabrication of new jugs.

Fabrication:

During the fabrication phase, finished materials (PET, stainless steel, PP, glass) undergo fabrication processes that convert the materials into containers. See **Appendix B** for details on fabrication processes. As stated above, it is assumed that container fabrication associated with bottled water occurs on-site at a bottling facility.

Municipal Water Treatment:

The source of the drinking water for the HOD bottled water systems differs by variant. For those variants that use municipal water for bottling, this phase encompasses the treatment of water at a municipal water treatment plant and subsequent distribution to a bottling facility. See **Appendix D** for details on the municipal treatment of drinking water.

Bottling Operations:

This phase represents operations at a bottling plant, including water treatment, container washing and container filling. The technologies employed for treating the water varies by the source of the water. In this study bottlers source their water from either municipal or natural (spring) supplies. Municipally sourced water will undergo microfiltration and reverse osmosis treatment (RO), followed by ozone treatment and UV disinfection. The treatment of water from natural sources, on the other hand, begins with micro-filtration followed by ozone treatment and UV disinfection. Naturally sourced water does not go through the RO process.

Filled Container Distribution:

This phase represents the transportation of filled 5-gallon jugs to a consumer household as part of an HOD distribution system. Also included in this phase is the transportation of empty jugs back to the bottling plant. Transportation burdens are based on ton-kilometers (metric tkm), and include mass of the container and water.

Residential Washing:

This phase represents the washing of the reusable drinking vessel in a residential dishwasher. The baseline scenario assumes the reusable container is washed after every four uses. Sensitivities are run to determine the life-cycle impacts associated with more frequent washing. See **Appendix F** for details on the residential washing process, and **Appendix I** for sensitivity analysis. This phase includes burdens associated with residential dishwashing including energy and water use for operation as well as energy use for wastewater treatment of the effluent.

Use:

The use phase represents the consumption of the drinking water at the consumer household. No life-cycle processes are explicitly represented during this phase.

Container Washing:

This phase represents the washing of reusable 5-gallon jugs at the bottling plant. The container washing occurs as a step in the bottling process, and thus the burdens associated with washing are represented in the bottling operations phase. The washing step involves the energy requirement for operation (electricity) and for heating the wash water to 60C (natural gas). See **Appendix E** for details of the bottling process.

Disposal:

Disposal includes the end of life fate of containers (5-gallon jugs, reusable drinking vessel). Primary containers, 5-gallon jugs, are subject to alternative end of life scenarios (recycling, land filling) depending on the variant under consideration. Disposal burdens include those associated with transportation from consumer to final disposal and process related burdens of recycling and landfill disposal. Disposal of the stainless steel bottle/cap and glass cup is split between recycling and land fill disposal based on the EPA estimates for municipal solid waste disposal in the US for various materials. See **Appendix H** for details regarding end-of-life processes.

3.2 HOD Bottled Water System Variants For Analysis

Variants of the HOD bottled water system were derived to represent a range of life-cycle impacts based on key life-cycle parameters. The variants cover the possible spectrum between minimum and maximum impacts without taking into consideration every possible combination of model parameters. Rather, variants are intended to highlight some of the trade-offs and important parameters of the life-cycle of HOD bottled water. Parameters used to construct variants include:

- **Primary Packaging** (5-gallon jug)**:** virgin-PET; PET w/ 25% recycled content; Polycarbonate.
- **Water Source:** Spring (natural source); municipal supply.
- **Reusable Drinking Vessel:** stainless steel bottle, glass cup.

- **Distribution Distance Allocation** (1-way)**:** 10 miles, 20 miles.
- **Disposal (jug):** Recycled, land fill disposal.

	1	2	3	4	5	6
Package:	PC	PC	PC	PET - virgin	PET-25% recy. cnt.	PC
Water Source:	Spring	Spring	Municipal	Spring	Spring	Spring
Reusable Drinking Vessel	Stainless steel bottle (18 oz.)	Glass cup (12 oz.)	Stainless steel bottle (18 oz.)	Stainless steel bottle (18 oz.)	Stainless steel bottle (18 oz.)	Stainless steel bottle (18 oz.)
Travel (miles, 1-way):	10	10	10	10	10	20
Disposal (jug):	Recycled	Recycled	Landfilled	Landfilled	Recycled	Recycled

Figure 3.2: Home and Office Delivery System Variants

Variant 1: PC jug; spring water; stainless steel bottle; jug recycled

Variant 1 represents a HOD system using a polycarbonate 5-gallon jug filled with spring water. Filled containers travel 10 miles in a delivery van to the consumer household as part of the delivery system. Water is served in the reusable drinking vessel, a stainless steel bottle. Empty container are collected as part of the delivery system and transported 10 miles back to the bottling facility to be reused. After 50 reuses, the 5-gallon jug is recycled.

Variant 2: PC jug; spring water; glass cup; jug recycled

Variant 2 replaces the stainless steel drinking vessel with a 12 oz. glass cup. This variant is intended to highlight the trade-off associated with the choice of a reusable drinking vessel.

Variant 3: PC jug; municipal water; steel bottle; jug landfilled

Variant 3 differs from variant 1 in the source of drinking water and end-of-life fate of containers. Here drinking water is sourced from municipal supplies, and 5-gallon jugs are land filled after 50 reuses. This variant is intended to highlight the differences in life-cycle impacts associated with the source of drinking water and the trade-off between recycling and land filling for a HOD bottled water system.

Variant 4: Virgin PET jug; spring water; steel bottle; jug landfilled

Variant 4 introduces the use of virgin-PET in the 5-gallon jug. This variant is intended to highlight the difference in life-cycle impacts of a HOD system with regards to material composition of the 5-gallon jug.

Variant 5: **rPET jug (25%); spring water; steel bottle; jug recycled**

Variant 5 uses 25% rPET in the 5-gallon jug, and introduces the benefit of recycled content and recycling to the HOD system.

Variant 6: **PC jug; spring water; steel bottle; jug recycled; extended distribution distance**

Variant 6 increases the one-way distribution distance from 10 to 20 miles, to determine the impact of distribution distance on the life-cycle impacts of HOD bottled water.

3.3 Results

Using SimaPro 7 LCA software and Microsoft Excel, the life-cycle impacts of Home and Office Delivery Bottled Water variants were evaluated. Results were evaluated in terms of 1000 gallons of drinking water delivered (4 PC jugs/50 reuses or 8 PET jugs/25 reuses) are presented by variant in Table 3.1 below, as defined in *section 3.2*.

Table 3.1: Combined Results By Variant

HOD Systems (1000 Gallons)

[1000 gallons = 3785.4 liters]	Variant					
	1	2	3	4	5	6
Energy (MJ)						
Jug Prod'n	413.55	413.55	413.55	607.68	523.19	413.55
Bottling	922.92	922.92	1177.20	922.92	922.92	922.92
Distribution	300.93	300.93	300.93	300.93	300.93	601.94
Reusable Ctr (life-cycle)	44.90	8.00	44.90	44.90	44.90	44.90
Washing (residential)	933.33	1400.00	933.33	933.33	933.33	933.33
End-of-Life (containers)	0.00	0.00	0.60	1.16	0.00	0.00
Total:	**2615.63**	**3045.40**	**2870.50**	**2810.92**	**2725.27**	**2916.63**
Solid Waste (kg)						
Jug Prod'n	0.45	0.45	0.45	0.26	0.77	0.45
Bottling	8.21	8.21	10.49	8.21	8.21	8.21
Distribution	0.00	0.00	0.00	0.00	0.00	0.00
Reusable Ctr (life-cycle)	0.03	0.67	0.03	0.03	0.03	0.03
Washing (residential)	9.23	13.84	9.23	9.23	9.23	9.23
End-of-Life (containers)	0.00	0.00	2.92	5.85	0.00	0.00
Total:	**17.92**	**23.18**	**23.13**	**23.57**	**18.23**	**17.92**
GWP (kg CO_2 eq)						
Jug Prod'n	22.32	22.32	22.32	25.50	22.86	22.32
Bottling	53.17	53.17	69.05	53.17	53.17	53.17
Distribution	22.56	22.56	22.56	22.56	22.56	45.12
Reusable Ctr (life-cycle)	2.51	0.59	2.51	2.51	2.51	2.51
Washing (residential)	54.93	82.40	54.93	54.93	54.93	54.93
End-of-Life (containers)	0.00	0.00	0.84	1.13	0.00	0.00
Total:	**155.49**	**181.04**	**172.21**	**159.80**	**156.03**	**178.05**
Water Use (gallons):						
Jug Prod'n	3.09	3.09	3.09	5.40	5.40	3.09
Bottling	264.20	264.20	597.50	264.20	264.20	264.20
Washing (residential)	213.30	320.00	213.30	213.30	213.30	213.30
Power Production	295.69	370.32	321.64	307.19	306.66	295.69
Transportation	3.00	3.00	3.00	3.00	3.00	6.00
Total:	**779.28**	**960.61**	**1138.53**	**793.09**	**792.56**	**782.28**

3.3.1 Life-Cycle Energy

Figure 3.3 displays life-cycle energy use results which range from **2,616 MJ** to **3,045 MJ**:

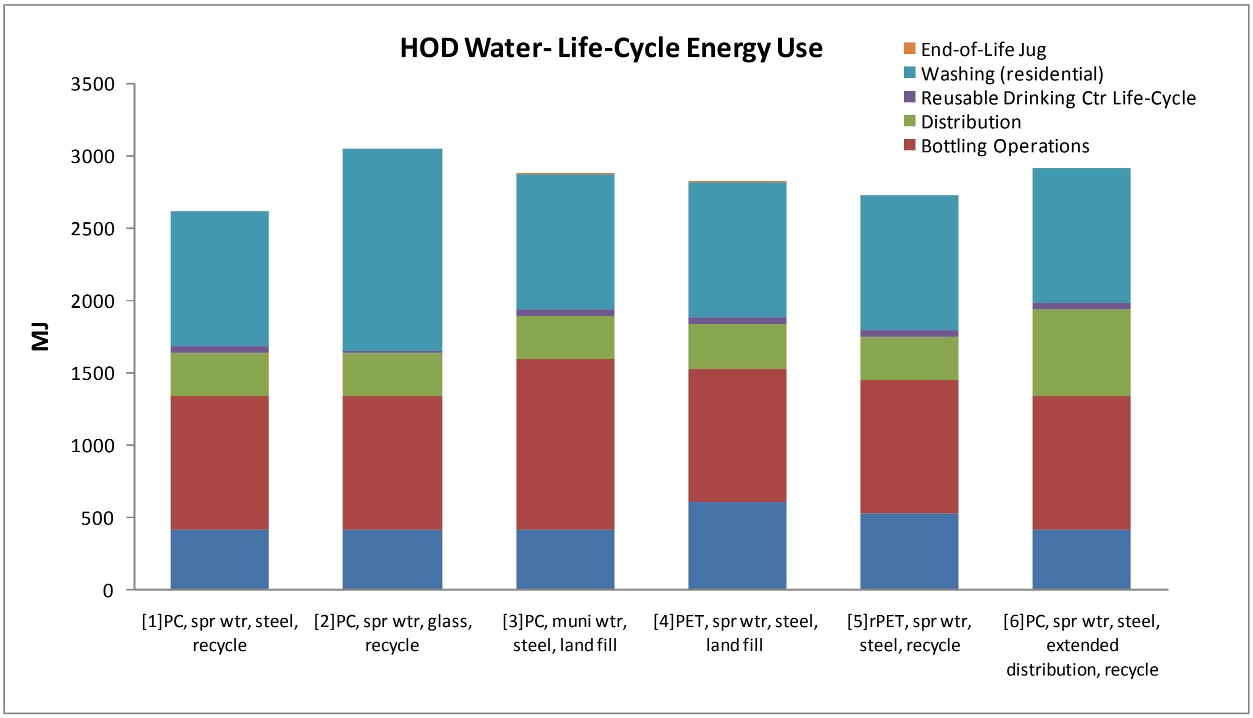

Figure 3.3: Life-Cycle Energy Use by Variant

Variant 1: PC jug; spring water; stainless steel bottle; jug recycled

Life-cycle energy is dominated by residential washing of the reusable stainless steel bottle and the operations at the bottling plant. These two life-cycle stages account for 36% and 35% of total life-cycle energy respectively. HOD bottling energy use for spring water is somewhat higher than for single-use bottled water from Chapter 2 (922.9 MJ vs. 687.6 MJ). This is due to the washing of the reusable 5-gallon jugs that is a part of the bottling process. The washing process consumes electricity for operation as well as natural gas to heat the washing water to 60C. Material production of the polycarbonate jug and distribution account for 16% and 12% of life-cycle energy respectively, while the life-cycle of the reusable stainless steel bottle (production, distribution, disposal) accounts for a mere 2%.

Variant 2: PC jug; spring water; glass cup; jug recycled

Here we see an increase in residential washing energy use to 46% of life-cycle energy (from 36%). This is due to the size of the drinking vessel. The 12 oz. glass cup requires more uses to consume 1000 gallons of drinking water (relative to the 18 oz. steel bottle) and thus undergoes more washing cycles (washed every 4 uses) and as such consumes more life-cycle energy. Energy from the reusable drinking container life-cycle has dropped from Variant 1 (from 44.9 MJ to 8.0 MJ). This is due to lower production energy for the glass cup relative to the stainless steel bottle.

Variant 3: PC jug; municipal water; steel bottle; jug landfilled

Here we observe a sharp increase in bottling energy use as it rises 6% to 41% of life-cycle energy use. This can be attributed to the use of municipal water for bottling. The life-cycle energy of municipal bottled water is greater than that of spring bottled water for two reasons: 1) municipal water has already been treated at a municipal treatment plant; 2) once it arrives at a bottling plant municipal water undergoes reverse osmosis treatment. Spring water does not undergo reverse osmosis at the bottling plant. Energy associated with end-of-life of 5-gallon jugs has increased slightly due to collection and transportation of the jugs to a landfill.

Variant 4: Virgin PET jug; spring water; steel bottle; jug landfilled

The key change in life-cycle energy relative to previous variants is related to the production of 5-gallon jugs. Per kg, manufacturing PET jugs is less energy intensive than PC jugs (104 MJ/kg vs. 141.5 MJ//kg); however, this system requires the use of twice the number of jugs as PC variants. As such, energy from jug production increases to 607.7 MJ (from 413.5 MJ), accounting for 22% of life-cycle energy.

Variant 5: rPET jug (25%); spring water; steel bottle; jug recycled

With the introduction of rPET, the key change in life-cycle energy is a decrease in jug production energy relative to Variant 4. Here jug production drops to 523.2 MJ (from 607.7 MJ) and accounts for 19% of life-cycle energy (from 22%). While rPET jugs are less energy intensive than those of virgin-PET, total jug production energy is still higher than that of PC jugs when accounting for the number of jugs required for the delivery of 1000 gallons of drinking water.

Variant 6: PC jug; spring water; steel bottle; jug recycled; extended distribution distance

The key change from Variant 1 is a marked increase in distribution energy use resulting from a doubling of the allocated one-way distance. Distribution energy increases to 601.9 MJ and 21% of life-cycle energy (from 300.9 MJ and 12%). Other values remain unchanged from Variant 1.

3.3.2 Life-Cycle Solid Waste

Figure 3.4 displays life-cycle solid waste results which range from **17.9 kg** to **23.6 kg**:

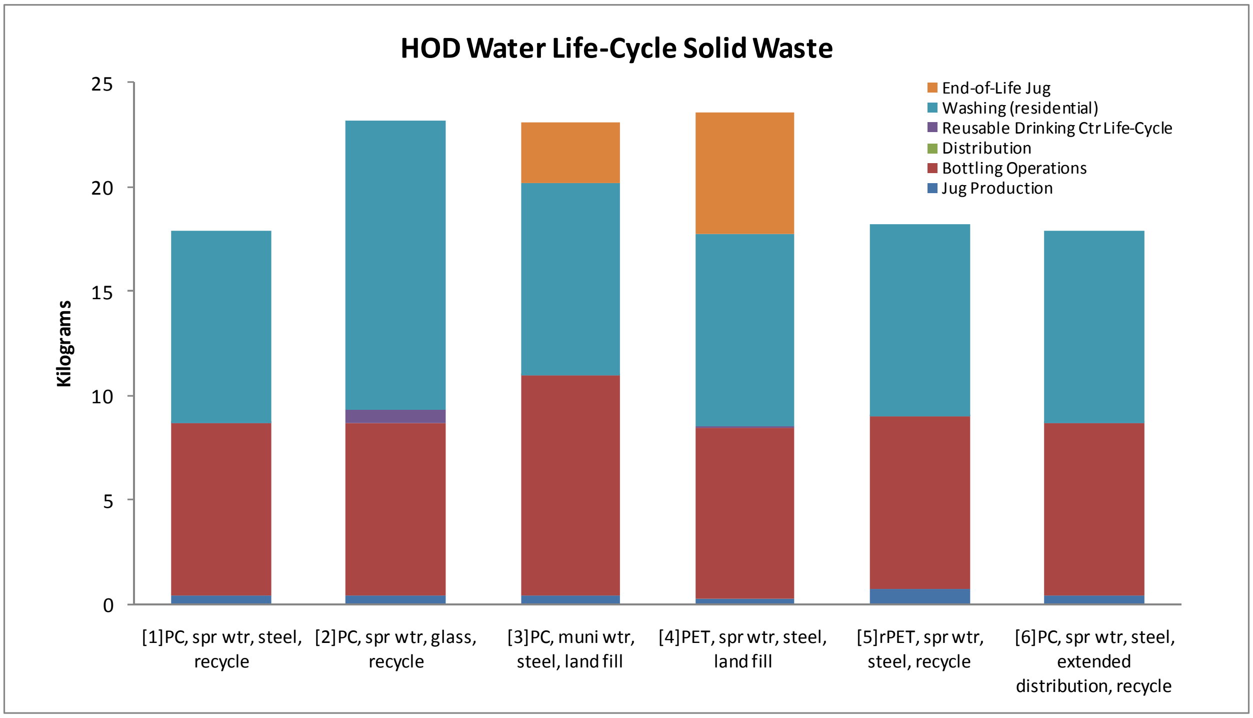

Figure 3.4: Life-Cycle Solid Waste by Variant

Variant 1: PC jug; spring water; stainless steel bottle; jug recycled

Much life life-cycle energy, solid waste is dominated by residential washing and bottling at 52% and 46% of the life-cycle. These are process related solid wastes associated with energy use. Solid waste from material production of the 5-gallon jug generates 3% of the life-cycle solid waste while the life-cycle of the reusable stainless steel bottle accounts for 0.2%.

Variant 2: PC jug; spring water; glass cup; jug recycled.

The increase in solid waste from residential washing relative to Variant 1 (13.8 kg vs. 9.2 kg) is due to the size of the drinking vessel and the increase in the number of required washing cycles. Also, we observe an increase in the solid waste generated from the life-cycle of the reusable drinking vessel. While less energy intensive, the production of the glass cup produces more solid waste than that of the stainless steel bottle. Further, landfill disposal of the glass cup adds additional solid waste to the life-cycle. Other life-cycle stages remain unchanged from Variant 1.

Variant 3: PC jug; municipal water; steel bottle; jug landfilled

A rise in solid waste from the bottling process can be attributed to the bottling of municipal water and the resulting increase in energy use and associated solid wastes. The use of municipal water for bottling increases bottling operation solid waste from 8.2 kg to 10.4 kg. The increase in solid waste from the end-of-life of containers is due to the land filling of 5-gallon polycarbonate jugs. The recycling from previous variants diverted the jug material while here we see 2.9 kg of post-consumer solid waste being deposited in a land fill.

Variant 4: Virgin PET jug; spring water; steel bottle; jug landfilled

Key values for this variant include solid waste from the manufacturing of 5-gallon jugs and post-consumer solid waste. Per kilogram, the production and manufacture of jugs from PET generates less solid waste than from PC. Consequently, while twice as many PET jugs are produced than would be with PC, the net generation of solid waste decreases to 0.3 kg (from 0.5 kg), and accounts for 1% of life-cycle solid waste. Post-consumer solid waste sent to a land fill (5-gallons jugs) has doubled from the previous variant, due to the use of twice as many jugs.

Variant 5: rPET jug (25%); spring water; steel bottle; jug recycled

We observe a marked increase in solid waste associated with jug production. This is due to the fact that process related solid wastes are greater for producing rPET bottles than virgin-PET, a consequence of the recycling methodology chosen for this study. End-of-life solid waste has dropped to zero as post-consumer solid waste is diverted from the land fill through recycling.

Variant 6: PC jug; spring water; steel bottle; jug recycled; extended distribution distance

Life-cycle solid waste remains unchanged from Variant 1.

3.3.3 Life-Cycle Greenhouse Gas Emissions

Figure 3.5 displays life-cycle greenhouse gas emission results which range from **156 kg CO_2eq** to **181 kg CO_2eq**:

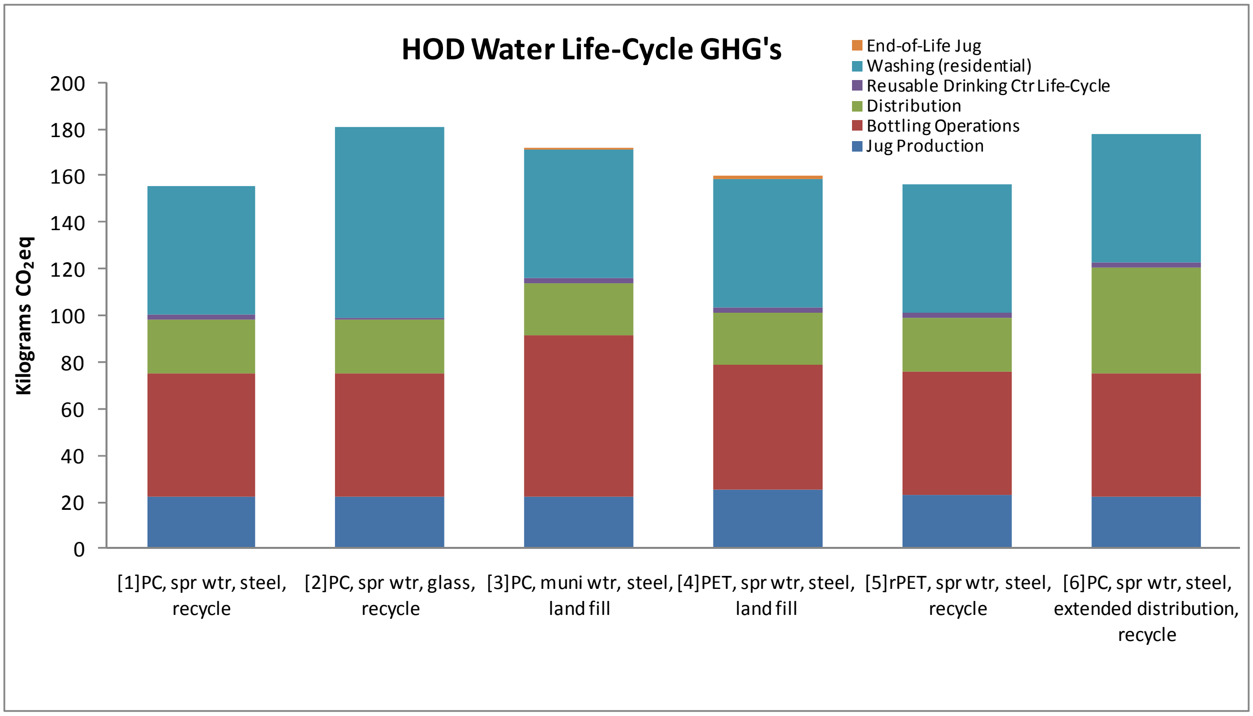

Figure 3.5: Life-Cycle GHG Emissions by Variant

Variant 1: PC jug; spring water; stainless steel bottle; jug recycled

Residential washing and bottling operations continue to dominate life-cycle impacts, at 35% and 34% of GHG emissions respectively. Emissions from distribution and material production are nearly equal at 14% and 14% respectively.

Variant 2: PC jug; spring water; glass cup; jug recycled

Again we observe a rise in impacts associated residential washing due to the size of the reusable drinking vessel as this stage accounts for 46% of GHG emissions (from 35% for Variant 1). In line with a decrease in energy use from the reusable drinking vessel life-cycle is a drop in GHG emissions from this stage to 0.6 kg CO_2eq and 0.3% of life-cycle emissions (from 2.5 kg CO_2eq and 2%). Emissions from other life-cycle stages remain unchanged from Variant 1.

Variant 3: PC jug; municipal water; steel bottle; jug landfilled

Relative to Variant 1, we observe increases in life-cycle GHG emissions associated with the bottling process and the end-of-life of 5-gallon jugs. As mentioned above, the life-cycle energy of municipal bottled water is greater than that of spring bottled water, and this translates into higher GHG emissions. The rise in GHG emission from the end-of-life of 5-gallon jugs is due to the collection and transportation of post-consumer solid waste to the land fill.

Variant 4: Virgin PET jug; spring water; steel bottle; jug landfilled

Key values here include GHG emissions from the production of and the end-of-life treatment of the 5-gallon jugs. The increase in production related GHG emissions is due to the use of 8 jugs (versus 4 with the PC variants). Further, after 25 reuses, the jugs are collected and transported to a land fill. As such, twice as much material is delivered to the land fill (relative to PC variants), and a commensurate rise in GHG emissions is observed.

Variant 5: rPET jug (25%); spring water; steel bottle; jug recycled

Commensurate with life-cycle energy, the use of rPET in the 5-gallon jugs yields a decrease in GHG emissions from Variant 4 as it drops to 22.9 kg CO_2eq and 15% of life-cycle emissions (from 22.5 kg and 16%). The diversion of post-consumer solid waste from the land fill decreases end-of-life emissions to zero. Other values remain unchanged from Variant 4.

Variant 6: PC jug; spring water; steel bottle; jug recycled; extended distribution distance

Like energy use, the key change from Variant 1 is a marked increase in distribution related emissions resulting from a doubling of the allocated one-way distance. GHG emissions from distribution increase to 45.12 kg CO_2eq and 25.3% of life-cycle emissions from 22.56 kg CO_2eq and 14.5%. Other values remain unchanged from Variant 1.

3.3.4 Life-Cycle Water Use

Figure 3.6 displays life-cycle water use results which range from **782 gallons** to **1139 gallons**:

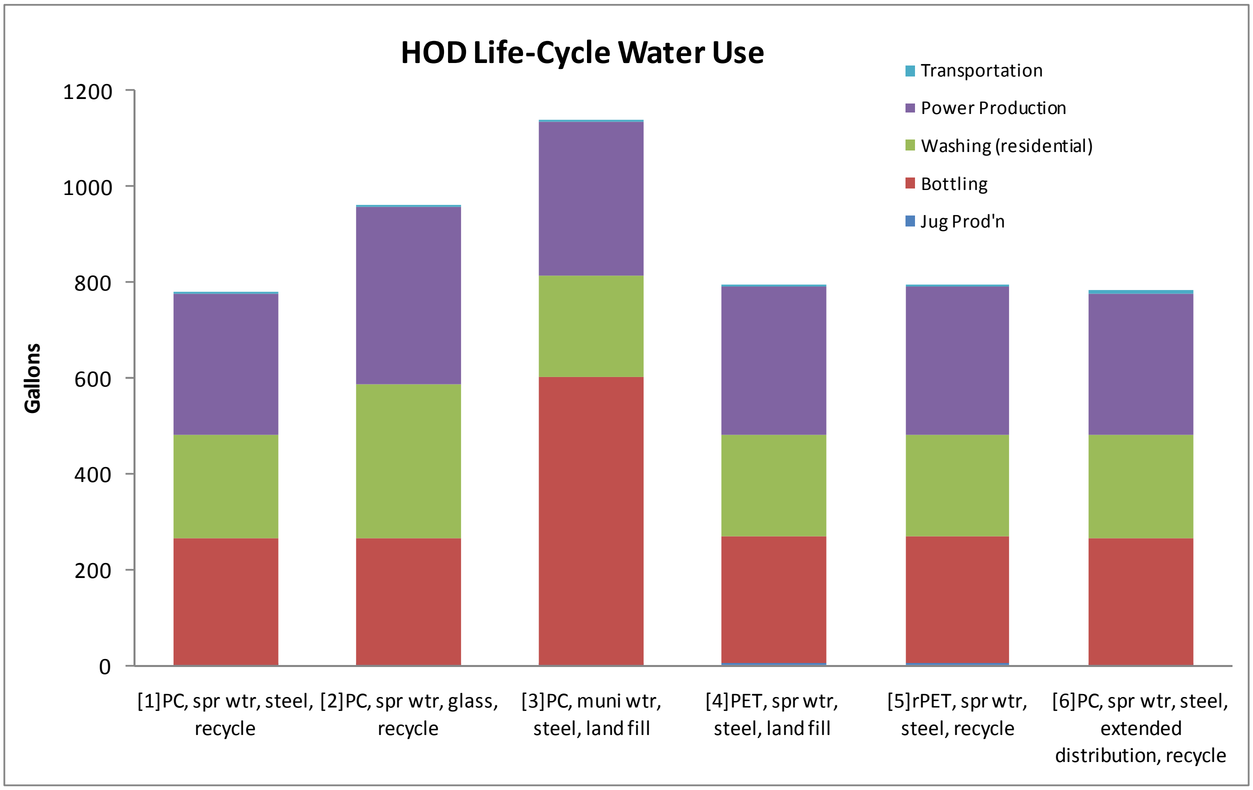

Figure 3.6: Life-Cycle Water Use by Variant

Variant 1: PC jug; spring water; stainless steel bottle; jug recycled

Life-cycle water use is dominated by power production followed by bottling operations at 38% and 34% respectively. The washing and rinsing procedures that occur during the HOD bottling procedure generates 1 liter of wastewater per 1 gallon of fill water, amounting to 264.2 gallons per 1000 gallons fill. Periodic residential washing of the stainless steel bottle (after every 4 uses) generates 213.3 gallons of wastewater, and 27% of life-cycle water use. Water use associated with material production is quite low relative to the single-use bottled variants in Chapter 2 (3.1 vs. 109.1 gallons). With 50 reuses per 5-gallon polycarbonate jug, considerably less material is required to delivery 1000 gallons of drinking water to consumers relative to single-use bottled water.

Variant 2: PC jug; spring water; glass cup; jug recycled

Attributable to the size of the reusable drinking vessel and the resultant increase in the number of required washing cycles is increase in water use from residential washing (from 213.3 to 320 gallons). Energy consumption required for additional washing cycles leads to an increase in water use from power production. Water use from jug production and bottling remains unchanged.

Variant 3: PC jug; municipal water; steel bottle; jug landfilled

Again, the use of municipal water for bottling yields a substantial increase in life-cycle impacts. Here were see an additional use of 333.3 gallons of water over the spring water variants for a total of 597.5 gallons of water use associated with bottling. This is related to the use of reverse-osmosis to treat municipal water at the bottling plant. Reverse-osmosis produces 25% wastewater, and thus requires the treatment of 1333.3 gallons to produce 1000 gallons of drinking water. This variant shows the highest life-cycle water use of all the HOD variants.

Variant 4: Virgin PET jug; spring water; steel bottle; jug landfilled

A key change to water use with this variant is the increase associated with production of the 5-gallon jug. Per kilogram, higher water use is associated with the production of PC jugs relative to PET jugs; however, due to the use of twice as much PET (more jugs), the jug production water use is higher overall for the PET variant.

Variant 5: rPET jug (25%); spring water; steel bottle; jug recycled

Water use remains unchanged from the previous variant.

Variant 6: PC jug; spring water; steel bottle; jug recycled; extended distribution distance

Transportation related water use increases slightly here from the previous variant due to the increased distribution distance.

3.4 Discussion

As evidenced by the analysis of HOD bottled water variants, several key factors determine the life-cycle impacts of an HOD system: washing of the reusable drinking vessel, type of water to be bottled, material composition of the 5-gallon jug, the end-of-life treatment of those jugs, and the distribution distance.

Generally the largest contributor to all life-cycle impact categories (excepting Variant 3), washing of the reusable drinking vessel ranges from 32-46% of life-cycle energy, 39.1-61.4% of life-cycle solid waste and 30.4-45.5% of life-cycle GHG emissions. This study assumes that the reusable drinking vessel will be washed after every four uses. Some consumer may choose to wash their drinking vessel more and some less, and this choice could have significant implications for life-cycle impacts. Sensitivity analysis was conducted to determine the effect on life-cycle impacts of frequency of washing (see **Appendix I**). Washing every four uses was assumed to be a suitable estimate for the baseline variants in this study. The type of water to be bottled is a factor in the life-cycle impacts of the HOD system. Bottling municipal water leads to an increase in life-cycle impacts in all categories relative to spring water variants. In fact, the use of municipal water (Variant 3) results in bottling becoming the dominant life-cycle process over residential washing of the reusable drinking vessel at 41% of life-cycle energy, 45.4% of life-cycle solid waste and 40.2% of life-cycle GHG's.

The material composition of the primary container (5-gallon jug) is a factor influencing the life-cycle energy and greenhouse gas profile of HOD bottled water. The advantage to using a polycarbonate jug is its durability and the resulting average 50 reuses per jug. More reuses translate into fewer containers per volume of delivered drinking water. As such this study assumes the use of 4 polycarbonate jugs versus 8 PET jugs (only 25 reuses) to deliver 1000 gallons of drinking water. Per kilogram, manufacturing jugs from PC is more energy, GHG and solid waste intensive than doing so from PET; however, the fewer number of PC jugs required more than offsets the difference rendering PC the better choice with respect to both energy use and GHG emissions.

The end-of-life treatment of the 5-gallon jugs has a significant influence on the life-cycle solid waste of the HOD system and particularly on end-of-life solid waste (post-consumer solid waste). Post-consumer solid waste ranges from 0% (jugs diverted from landfill via recycling) to 24.8% (virgin-PET jugs land filled) of life-cycle solid waste across variants. The recycling of 5-gallon jugs is crucial to improving the life-cycle solid waste profile of an HOD system.

Distribution distance is also a critical factor influencing the life-cycle impacts of HOD bottled water, particularly with respect to energy use and GHG emissions. With an increase in the one-way distribution distance from 10 to 20 miles, we observe distribution energy rise to 20.6% of life-cycle energy from 11.5%. With respect to GHG emissions, the increase in distance results in a rise in distribution related emission to 25.3% from 14.5%. Delivery routes should be optimized to minimize distribution distance to any one consumer household to reduce the life-cycle impacts of an HOD bottled water system.

Chapter 4

Municipal Tap Water

4.1 System Description

This system represents the delivery of drinking water to consumers via municipal water systems terminating in a household tap. At the household, the drinking water is consumed through the use of a reusable drinking vessel (stainless steel bottle, glass cup). Figure 4.1 shows the overview of the system model.

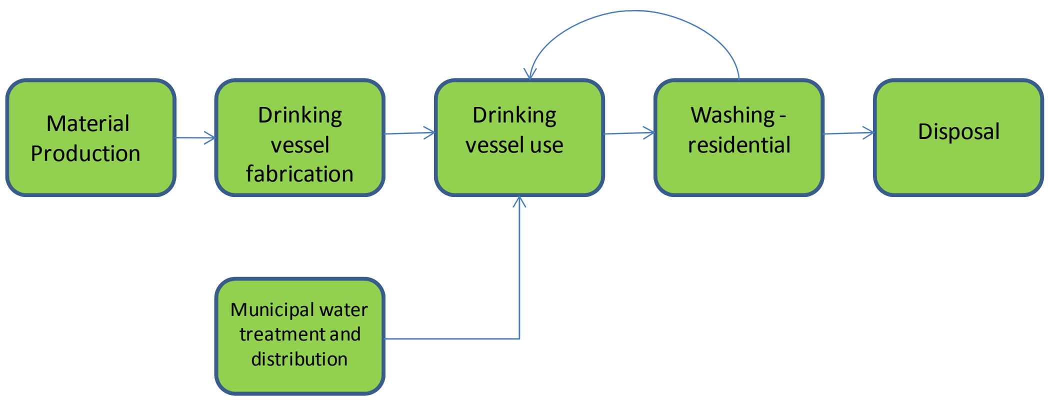

Figure 4.1: Overview of Life-Cycle System Model

The life-cycle begins with the conversion of raw materials into finished materials, in this case the production of stainless steel, polypropylene and glass, which are then used in the fabrication of the reusable drinking vessel (stainless steel bottle/cap, glass cup). Drinking water is treated and distributed via municipal systems to a consumer household. Drinking water is served in the reusable drinking vessel which is periodically washed in a residential dishwasher. The end-of-life disposal of the reusable drinking vessel is split between recycling and land fill disposal based on the EPA estimates for municipal solid waste disposal in the US for various materials.

The baseline scenario analyzes the use of two reusable drinking vessels (stainless steel bottle, glass cup) to consume the whole functional unit (1000 gallons of drinking water). Sensitivities are run to determine the life cycle impacts of shorter container life requiring the use of additional containers. See **Appendix I** for sensitivity analysis regarding container life and the use of additional reusable containers. The stainless steel bottle is manufactured in China and brought to the consumer by a combination of ocean freight and truck transport. The glass cup distribution distance was assumed to be 300 miles by diesel tractor trailer.

4.1.1 Life Cycle Processes

Material Production:

During the material production phase, raw materials are extracted from the earth and transformed into the desired finished materials. The material production phase for this system represents the material production activities for the reusable drinking vessel (stainless steel, glass) and cap (polypropylene). See **Appendix B** for details of material production processes.

Fabrication:

During the fabrication phase, finished materials (stainless steel, glass, PP) undergo fabrication processes that convert the materials into containers. See **Appendix B** for details on fabrication processes. This phase includes:

- Stainless steel container fabrication
- PP injection molding to produce cap
- Glass cup fabrication

Municipal Water Treatment and Distribution:

This phase encompasses the treatment at a municipal water treatment plant and subsequent distribution of 1000 gallons of drinking water to a consumer household. See **Appendix D** for details on the municipal treatment and distribution of drinking water.

Use:

The use phase represents the consumption of the drinking water at the consumer household. No life-cycle processes are explicitly represented during this phase.

Residential Washing:

This phase represents the washing of the reusable drinking vessel in a residential dishwasher. The baseline scenario assumes the reusable container is washed after every four uses. Sensitivities are run to determine the life-cycle impacts associated with more frequent washing. See **Appendix F** for details on the residential washing process, and **Appendix I** for the sensitivity analysis. This phase includes burdens associated with residential dishwashing including energy and water use for operation as well as energy use for wastewater treatment of the effluent.

Disposal:

Disposal includes the end of life fate of the reusable drinking vessel (stainless steel bottle, PP cap or glass cup). Disposal burdens include those associated with transportation from consumer to final disposal and process related burdens. Disposal of the stainless steel bottle/cap and glass cup is split between recycling and land fill disposal based on the EPA estimates for municipal solid waste disposal in the US for various materials. See **Appendix H** for details regarding end of life processes.

4.2 Tap water system variants

Relative to the single-use and HOD bottled water systems, the tap water system is straightforward, and not conducive to myriad variants. As such, only two variants on the life-cycle of a tap drinking water system are analyzed. The variants highlight life-cycle impacts relative to the choice of a reusable drinking vessel, either a stainless steel bottle or a glass cup. Sensitivities are also run to evaluate life-cycle impacts of different patterns of residential washing, and variation in container life requiring the use of additional reusable containers. See **Appendix I** for sensitivity analyses.

	1	**2**
Reusable Drinking Vessel	Stainless steel bottle (18 oz.)	Glass cup (12 oz.)
Distribution (miles):	6570/1500	300
Disposal: (% recy/% landfill)	63.3%/36.7%	28.1%/71.9%

Figure 4.2: Tap Water System Variants

Variant 1: Stainless steel bottle

Variant 1 represents tap water served in a reusable stainless steel 18 oz. bottle (based on the Klean Kanteen™ product). The bottle is assumed manufactured in China and transported 6570 miles from Shanghai to Long Beach, CA on an ocean freighter followed by 1500 miles of truck travel to reach the consumer market in the central United States. The steel bottle is subject to 63.3% recycling and 36.7% land fill disposal at the end of its useful life.

Variant 2: Glass cup

Variant 2 represents tap water served in a 12 oz. glass kitchen cup. Distribution distance for the glass cup was assumed to be 300 miles by diesel tractor trailer. The glass cup is subject to 28.1% recycling and 71.9% land fill disposal at the end of its useful life. This variant is intended to highlight the tradeoff involved in the selection of a reusable drinking vessel.

4.3 Results

Using SimaPro 7 LCA software and Microsoft Excel, the life-cycle impacts of Tap Water System Variants were evaluated. Results were evaluated in terms of 1000 gallons of delivered drinking water (using two reusable drinking vessels) and are presented by variant, as defined in *section 4.2* above.

Table 4.1: Combined Results By Variant

Municipal Tap Systems (1000 Gallons)

[1000 gallons = 3785.4 liters]	Variant	
	1	**2**
Energy (MJ)		
Municipal Water Trmnt	76.44	76.44
Reusable Ctr (life-cycle)	43.25	8.00
Washing (residential)	933.33	1400.00
Total:	**1053.02**	**1484.44**
Solid Waste (kg)		
Municipal water trmnt	0.58	0.58
Reusable ctr (prod'n, disp)	0.03	0.67
Washing (residential):	9.23	13.84
Total:	**9.84**	**15.10**
GWP (kg CO_2 eq)		
Municipal water trmnt	5.21	5.21
Reusable ctr (prod'n, disp)	2.39	0.59
Washing (residential):	54.93	82.40
Total:	**62.53**	**88.20**
Water Use (gallons):		
Washing Reusable Ctr	213.30	320.00
Power Production	152.48	227.11
Transportation	0.00	0.00
Total:	**365.78**	**547.11**

4.3.1 Life-Cycle Energy Use

Figure 4.3 displays life-cycle energy use results which range from **63 MJ** to **80 MJ**:

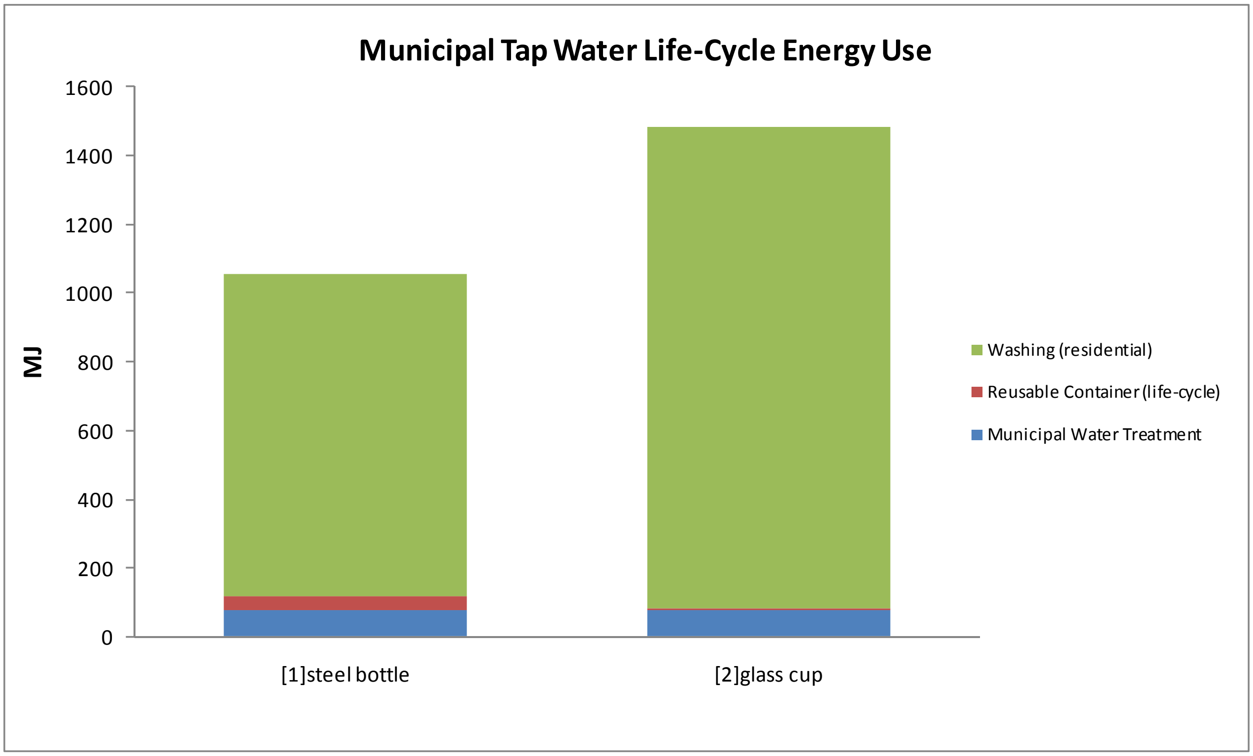

Figure 4.3: Life-Cycle Energy Use by Variant

Variant 1: Stainless steel bottle

The overwhelming majority of life-cycle energy of the tap water system is attributed to the residential dishwashing of the reusable stainless steel bottle. At 933.3 MJ washing energy accounts for 89%. The remaining life-cycle energy is a product of municipal water treatment (7%) and the life-cycle of the reusable bottle (4%).

Variant 2: Glass cup

Again, life-cycle energy use is dominated by residential dishwashing of the reusable drinking vessel. At 1400 MJ, washing accounts for 94% of life-cycle energy. The remaining energy use is from municipal water treatment (5%) and the life-cycle (production, disposal) of the glass cup (0.5%). Despite a lower contribution of life-cycle energy from the reusable container life-cycle relative to Variant 1 (glass cup less energy intensive than steel bottle) Variant 2 washing energy is considerable higher, and as a result has a greater total life-cycle energy use. This is related to the smaller size of the glass cup relative to the steel bottle, and the additional washing cycles required for the consumption of 1000 gallons of water, washing after every 4 uses.

4.3.2 Life-Cycle Solid Waste

Figure 4.4 displays life-cycle solid waste results which range from **9.8 kg** to **15.1 kg**:

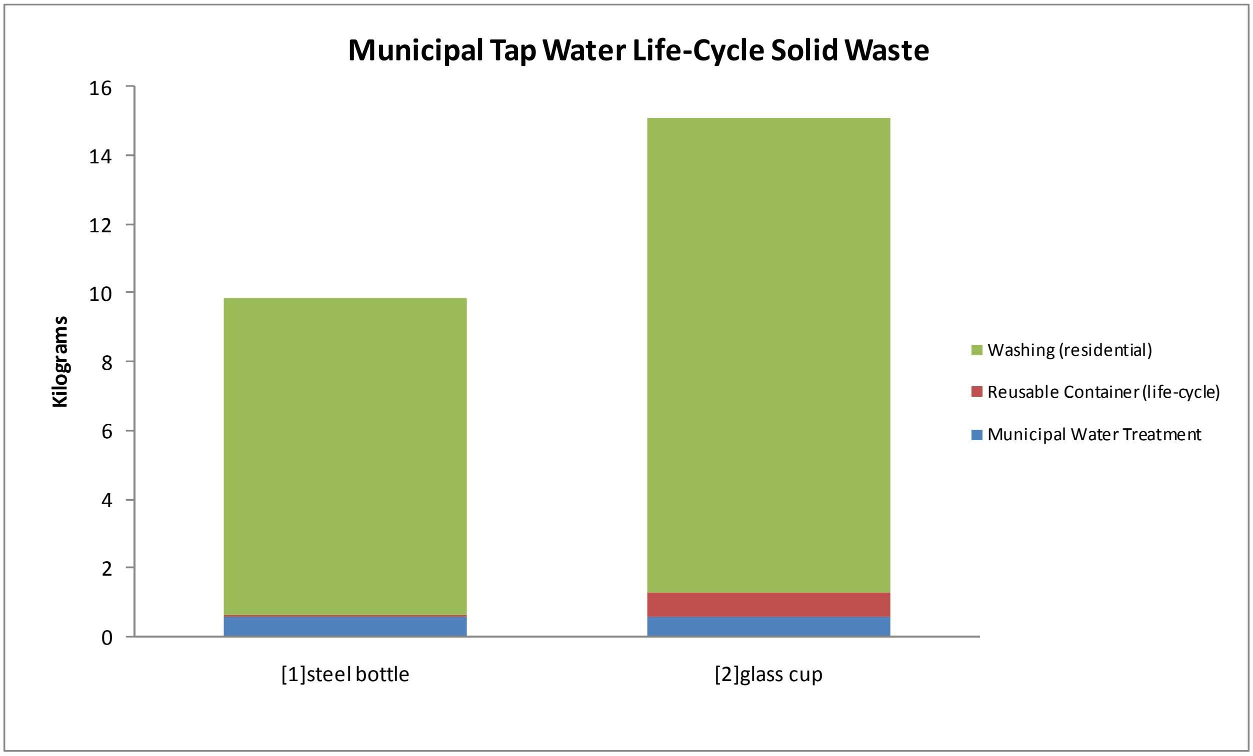

Figure 4.4: Life-Cycle Solid Waste by Variant

Variant 1: Stainless steel bottle

Residential washing accounts for the vast majority of life-cycle solid waste for the tap water system. At 9.2 kg, residential washing generates 94% of life-cycle solid waste. The remaining life-cycle solid waste is a product of municipal water treatment (6%) and the life-cycle of the reusable bottle (0.3%).

Variant 2: Glass cup

Residential washing generates the lion's share of life-cycle solid waste. At 13.8 kg, washing accounts for 92% of life-cycle solid waste. Municipal water treatment (4%) and the life-cycle of the glass cup (0.4%) are responsible for the remaining solid waste.

4.3.3 Life-Cycle Greenhouse Gas Emissions

Figure 4.5 displays life-cycle GHG emission results which range from 1,053 **kg CO_2eq** to **1,484 kg CO_2eq**:

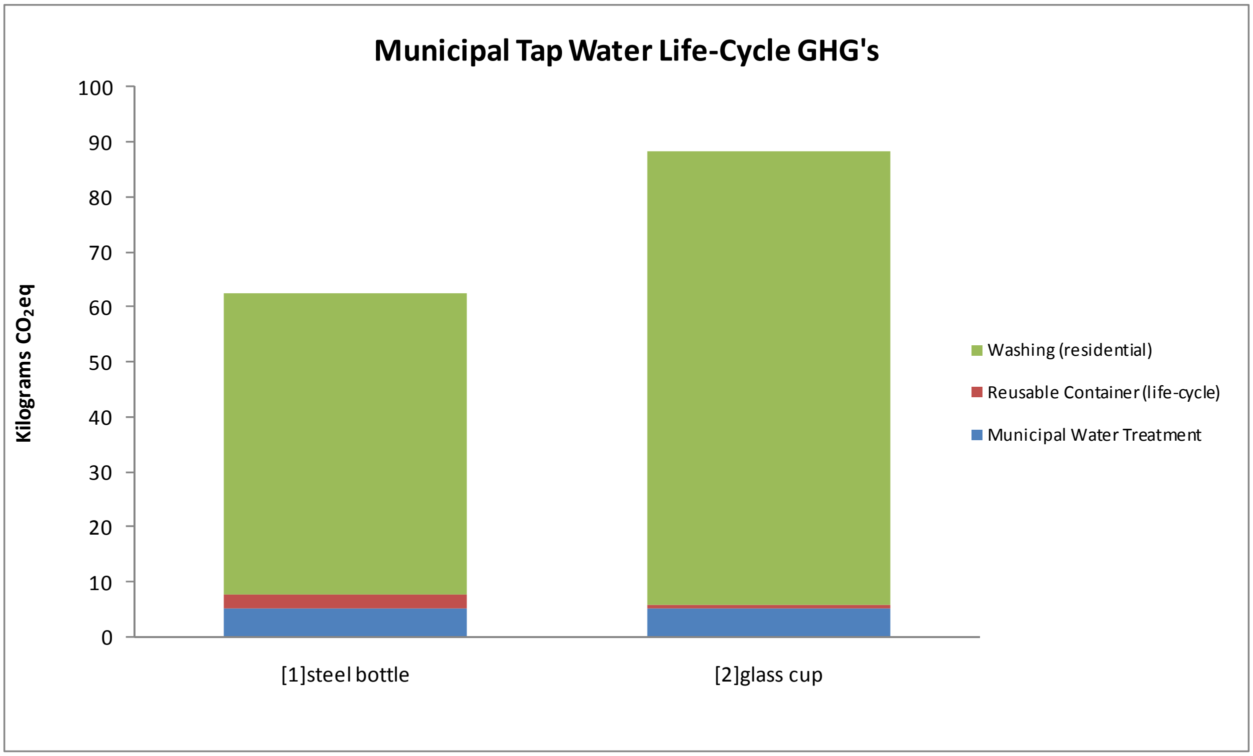

Figure 4.5: Life-Cycle GHG's by Variant

Variant 1: Stainless steel bottle

Residential washing contributes the majority of life-cycle greenhouse gas emissions for the tap water system. At 54.9 kg CO_2eq, residential washing generates 88% of life-cycle GHG's. The remaining emissions are a product of municipal water treatment (8%) and the life-cycle of the reusable bottle (4%).

Variant 2: Glass Cup

The bulk of life-cycle GHG emissions results from residential washing of the glass cup. At 82.4 kg CO_2eq, washing represents 93% of emissions. The remaining emissions come from municipal water treatment (6%) and the life-cycle of the glass cup (0.7%).

4.3.4 Life-Cycle Water Use

Figure 4.6 displays life-cycle water use results which range from **366 gallons** to **547 gallons**:

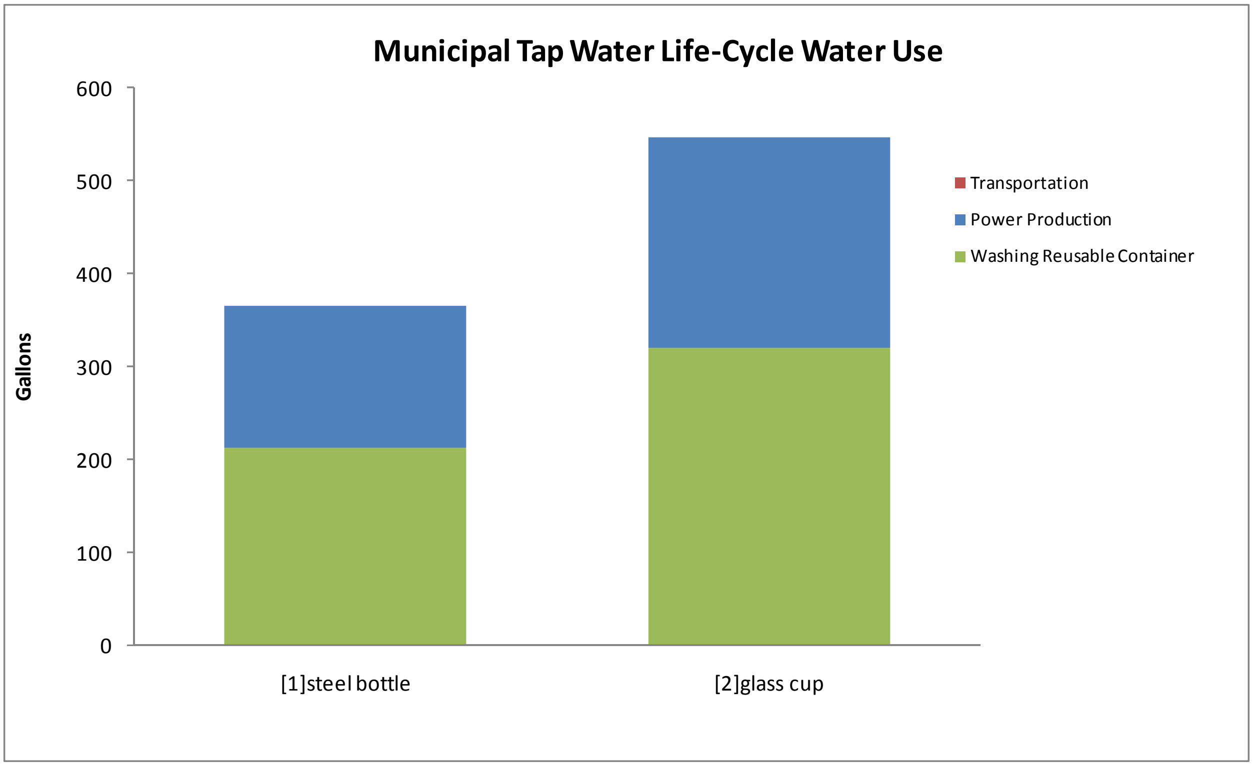

Figure 4.6: Life-Cycle Water Use by Variant

Variant 1: Stainless steel bottle

The majority of life-cycle water use (58%) associated with the tap water system is a product of the residential washing process. Over the course of consuming 1000 gallons of drinking water, 213.8 gallons of water are consumed for washing of the reusable bottle. Water used in power production accounts for the remaining water use.

Variant 2: Glass cup

Again, the majority of life-cycle water use associated with the tap water system is a product of the residential washing process. Over the course of consuming 1000 gallons of drinking water, 320 gallons of water are consumed for washing of the reusable bottle. Water use increases from Variant 1 due to the additional washing cycles required for the glass cup and the associated additional washing water and power production.

4.4 Discussion

As evidenced by the analysis of municipal tap water variants, the key factor that determines the life-cycle impacts is the washing of the reusable drinking vessel. For both tap water variants, washing is responsible for more than 87% of energy use, solid waste and GHG emissions, and 100% of water use. As such, Variant 1 outperforms Variant 2 in all impact categories because of the additional washing required by the smaller size of the glass cup. As stated above, this study assumes the reusable drinking vessel is washed after every 4 uses. Per use (refill), the 12 oz. glass cup delivers less water than the 18 oz. stainless steel bottle and thus requires more washing cycles to deliver the full functional unit of 1000 gallons of drinking water. In this respect, the choice of a reusable drinking vessel has an effect on the life-cycle impacts of tap water systems.

A comparison of the life-cycle impacts of the containers themselves shows, however, that the stainless steel bottle is considerably more intensive with respect to energy use and GHG emissions. The bottle uses more than five times the energy and emits more than 4 times the GHG's than the glass cup across the life-cycle. With regard to solid waste, however, the glass cup generates nearly two times the amount produced during the bottle across the life-cycle.

Chapter 5

Comparison of Systems

Figure 5.1 defines the parameters of the system variants discussed below:

B-1: Regional bottled, virgin-PET, spring water, landfilled.	H-1: PC jug, spring water, stainless bottle, recycled
B-2: Reg'l bottled, 25% rPET, spring water	H-2: PC jug, spring water, glass cup, recycled
B-3: Reg'l bottled, 25% rPET, municipal water	H-3: PC jug, municipal water, stainless bottle, landfilled
B-4: Reg'l bottled, PLA, spring water	H-4: virgin-PET jug, spring water, stainless bottle, lanfdilled
B-5: National bottled, 25% rPET	H-5: 25% rPET, spring water, stainless bottle, recycled
B-6: Overseas bottled, 25% rPET	H-6: PC jug, spring water, stainless bottle, extended distance
B-7: Extended overseas, virgin-PET	
T-1: Tap water, stainless bottle	
T-2: Tap water, glass cup	

Figure 5.1: Parameters of Systems Variants

5.1 Life-Cycle Energy Use

To allow for a relative comparison, **Figure 5.2** displays life-cycle energy use across all variants from each of the three systems.

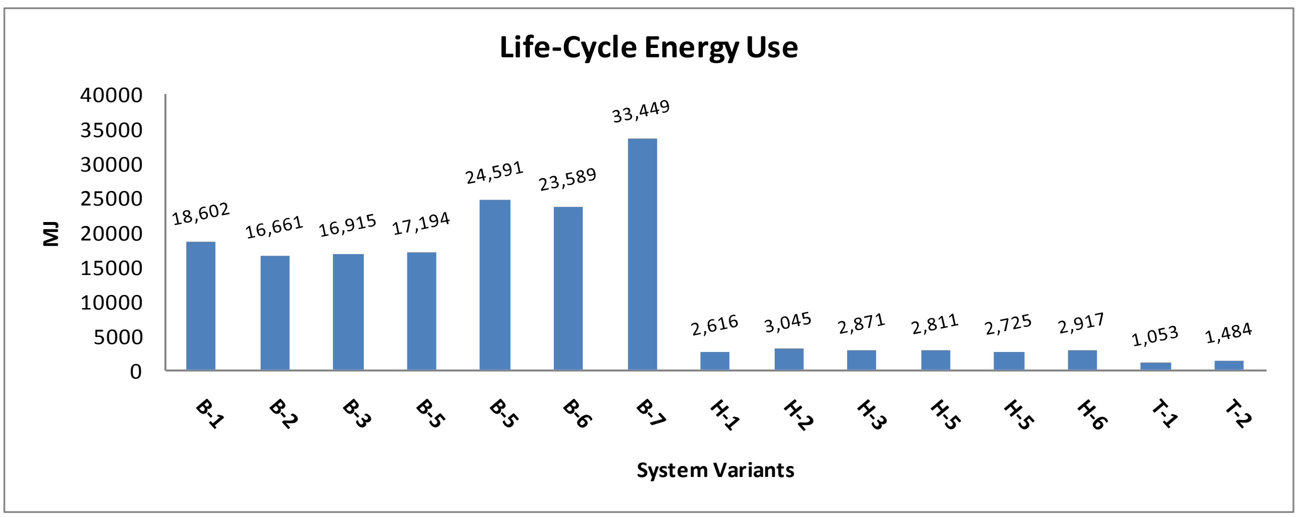

Figure 5.2: Life-Cycle Energy

With respect to energy use, the tap systems are clearly the preferable drinking water delivery system. Relative to tap water served in a reusable drinking vessel, single-use bottled systems have between **11-31** times higher use. Including recycled content in the bottles improves the performance of the bottled system relative to tap while increasing distribution distance makes the disparity more pronounced. The greatest difference in energy use comes from a comparison of the extended overseas bottled water with the tap system using the stainless steel bottle.

Relative to home and office delivery systems, the tap systems have between 35% and 55% of life-cycle energy use. Both the HOD and tap systems energy use are heavily determined by the residential washing of the reusable drinking vessel. What separates the systems is the energy use from jug production, bottling and distribution in the HOD systems.

A comparison of single-use bottled and HOD systems shows that HOD systems are preferable with respect to energy use by a wide margin. HOD systems use between 8% and 18% of the energy consumed by bottled systems. The key factor in the difference in energy is single-use bottle production at regional distances, joined by distribution energy for national and overseas bottled variants.

5.2 Life-Cycle Solid Waste

For relative comparison, **Figure 5.3** illustrates differences in life-cycle solid waste generation across all variants from each of the three systems.

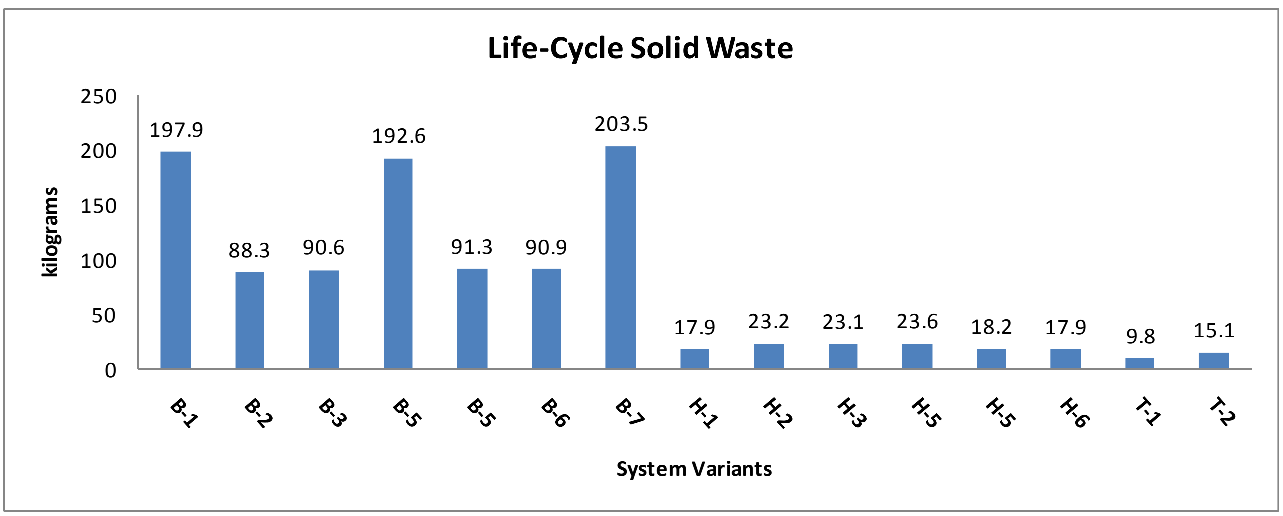

Figure 5.3: Life-Cycle Solid Waste

With respect to life-cycle solid waste generation, tap water systems are the preferred systems. Relative to tap water served in a reusable drinking vessel, single-use bottled systems generate between **6-21** times more solid waste. For single-use bottled systems the majority of solid waste comes from the end-of-life of containers and packaging and container production. For the tap systems, most of the waste is produced from the washing of the reusable drinking vessel, and is tied to the energy demands of dishwasher.

When compared to the home and office delivery systems, tap water shows between 42% and 81% of life-cycle solid. The disparity is less pronounced relative to energy use. Like the tap systems, the majority of solid waste from the HOD systems is a result of washing of the reusable drinking vessel (with one exception – Variant 3 is dominated by bottling due to the use of municipal water and the associated energy demands).

A comparison of single-use bottled and HOD systems shows that HOD systems are preferable with respect to life-cycle solid waste. HOD systems show between 9% and 27% of life-cycle solid waste of single-use bottled systems.

5.3 Life-Cycle Greenhouse Gas Emissions

For relative comparison, **Figure 5.4** highlights the differences in life-cycle greenhouse gas emissions across all variants from each of the three systems.

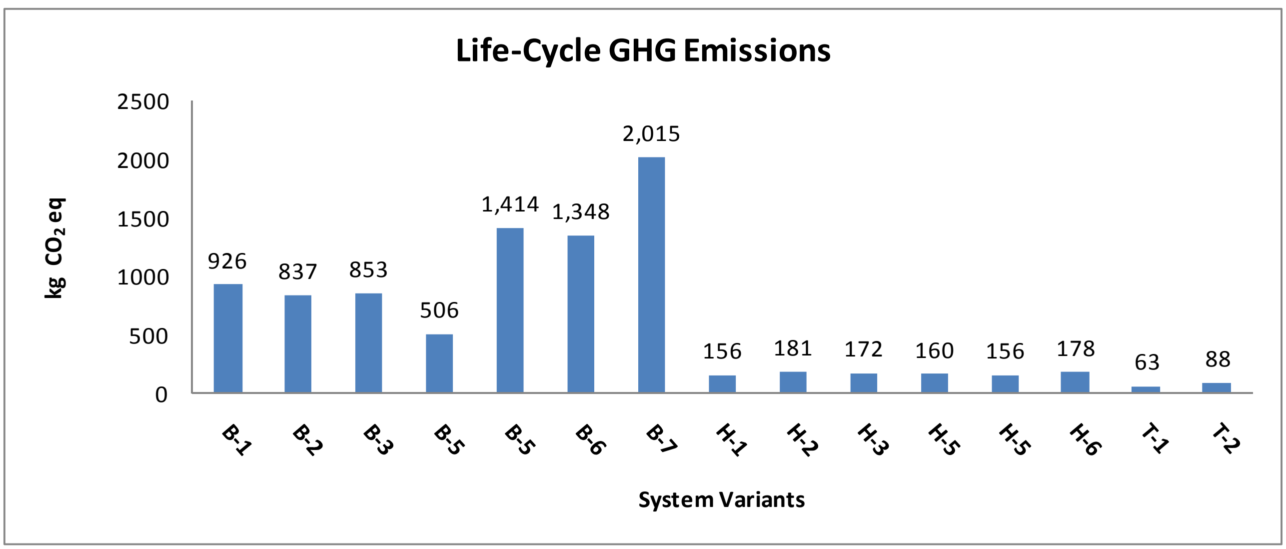

Figure 5.4: Life-Cycle GHG Emissions

With respect to life-cycle greenhouse gas emissions, tap water systems are the preferred systems. With respect to tap water served in a reusable drinking vessel, single-use bottled systems generate **6-32** times more GHG emission. For single-use bottled systems, regional systems are dominated by bottle production while for national and overseas systems distribution produces the majority of emissions. For tap systems, residential washing is responsible for the vast majority of emissions.

Compared with home and office delivery systems, tap water systems produce between 35% and 57% of life-cycle greenhouse gas emissions. The generation of GHG emissions is highly correlated with energy use, and similar to tap systems, the majority of emissions from the HOD systems are related to residential washing of the reusable drinking vessel. The difference in emissions here can be attributed to jug production, bottling operations and distribution in the HOD systems.

When single-use bottled and HOD systems are compared, we see that HOD systems produce between 8% and 31% of the life-cycle emissions of single-use systems. Separating the systems are the emission intensive single-use bottle production and distribution activities.

5.4 Life-Cycle Water Use

The differences in life-cycle water use are highlighted in **Figure 5.4** across all variants from each of the three systems.

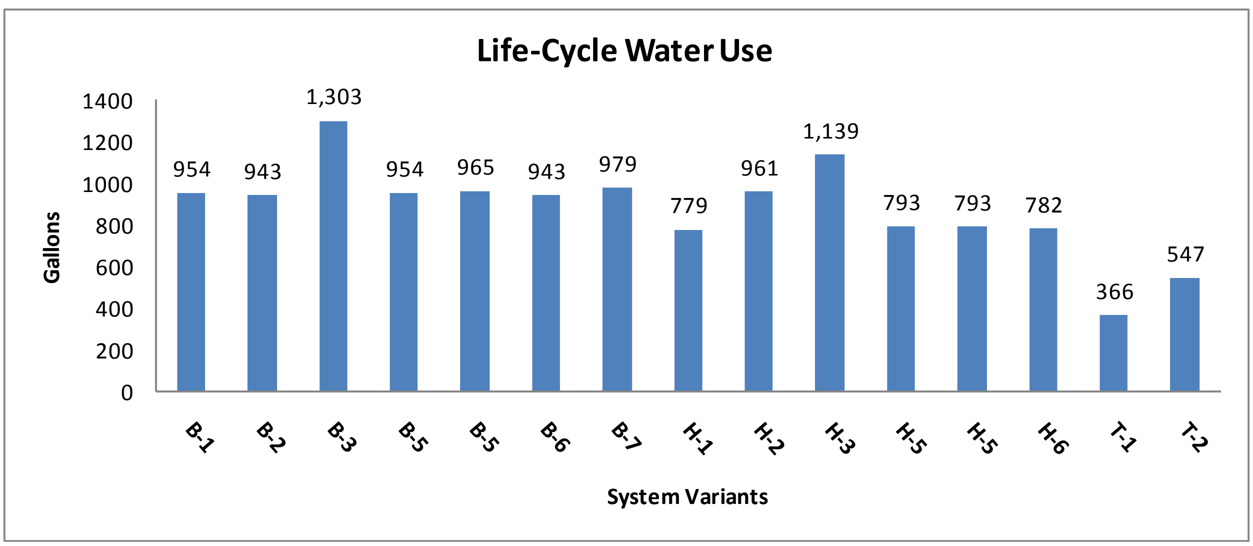

Figure 5.5: Life-Cycle Water Use

With respect to life-cycle water use, the municipal tap systems outperform both HOD and single-use bottled systems by a considerable margin. Single-use bottled systems consume large amounts of water indirectly through the power requirements of the systems. The HOD systems bottling process and associated power requirements separate them from municipal tap systems.

The HOD system water use is dominated by power production, bottling process as well as the residential washing of the reusable drinking vessel. Tap systems water use is dominated by residential washing. As such, water use in tap and HOD systems is determined at least in part by the number of residential washing cycles in the life-cycle which is a function of the choice of a reusable drinking vessel. Variants **H-2** and **T-2** illustrate the impact of choosing the smaller 12 oz. cup (as opposed to the 18 oz. bottle). With the assumed pattern of washing after every four uses, the glass cup is washed more times during the course of delivering 1000 gallons of drinking water and thus consumes more water for washing.

Bottling municipal water (variants **B-3** and **H-3**) increases water use substantially due to industry standard treatment procedure for municipal water. At the bottling plant, municipal water undergoes reverse-osmosis treatment, a process that generates 25% wastewater. Typically, spring water will not be subject to reverse-osmosis treatment. As such, the highest life-cycle water use is associated with variants **B-3** and **H-3** the systems that utilizes municipal water for bottling.

Aside from residential washing activities, it is the HOD bottling process that separates the single-use bottled and HOD systems. The single-use bottling process produces wastewater at 6.7% of fill water. The wastewater is water that has been used to rinse the bottles before filling. The HOD bottling process produce one liter of wastewater per 1 gallon of fill, or 26% wastewater relative to the volume bottled.

Chapter 6

Conclusions

6.1 Key Findings and Recommendations for Improvement

In all life-cycle impact categories the tap water systems outperformed both single-use bottled and HOD systems by a margin of at least **45.1%** and by as much as **96.9%**. As the tap water systems life-cycle impacts are essentially determined by the residential washing of the reusable drinking vessel, the energy, solid waste, greenhouse gas and water use profile can be improved by reducing dishwashing burdens, thereby more effectively leveraging their performance against the bottled systems. This can be accomplished by reducing the frequency of washing (decrease to every 6-8uses?) or reducing the burdens allocated to the drinking vessel by only washing when the dishwasher is loaded to capacity. The baseline scenario for this study assumes the drinking vessel will be washed after every 4 uses, and allocates 3% of dishwashing burdens to the tap water system. Washing less frequently and fully loading the dishwasher can substantially reduce life-cycle burdens attributed to residential washing. See **Appendix I** for a sensitivity analysis regarding the allocation of dishwashing burdens (energy, GHG's, solid waste).

With the exception of water use, the HOD systems perform significantly better than single-use bottled systems with respect to energy, solid waste and greenhouse gas emissions. HOD showed at most **31%** and as little as **7.7%** of the life-cycle impacts of single-use bottled systems across energy, solid waste and greenhouse gas emissions.

Like tap water systems, HOD systems can more effectively leverage their performance against single-use systems by reducing the burdens associated with residential dishwashing. With the exception of HOD Variant 3, under which municipal water is bottled, residential dishwashing is the dominant process contributing to all life-cycle impact categories for the HOD systems. Reducing the burdens associated with residential dishwashing has the potential to significantly mitigate life-cycle energy, solid waste, greenhouse gas emissions and water use. After residential washing, the HOD bottling process is the dominant contributor to life-cycle impacts of HOD systems.

Improvement in the bottling process aimed at reducing energy consumption and water use stand to significantly improve the life-cycle profile of HOD systems. Bottling municipal water proved to increase impacts in all categories, particularly with regard to water use. Further improvements in the life-cycle impact profile of HOD systems may be achieved should bottler opt to bottle only spring water.

Single-use bottled systems were the worst performers with regard to energy use, solid waste and greenhouse gas emissions by a wide margin. The production of petroleum based single-use bottles is the dominant contributor to energy use that is between **11-18 times** greater than that of tap water systems for regionally distributed bottled water. When the distribution of bottled water is extended to reach a national or international market, this difference grows to between **17-32 times** the energy use seen in tap water systems. Similar trends are seen in greenhouse gas emissions where regional bottled water life-cycle emissions are between **6-15 times** more than those from tap systems. For internationally distributed bottled water, these emission climb to **22-32 times** more than tap water systems. With regard to solid waste, the end-of-life treatment of containers is the dominant factor in life-cycle of single-use bottled water. Systems that send the empty bottles to a landfill generate roughly **14-20** times the solid waste of tap water systems, while those that employ the recycling of bottles reduce this difference to **6-9** times.

The life-cycle energy and greenhouse gas profile of single-use bottled systems have potential for improvement. First off, incorporating rPET (PET with recycled content) into the single-use bottles can significantly reduce container production energy, a dominant contributor to both life-cycle energy and GHG's. Significant energy and greenhouse gas benefits result from offsetting intensive virgin material production with the use of rPET. A **14%** drop in container production energy and **10%** drop in life-cycle energy were observed with introduction of rPET (25% recycled content) into the single-use bottled systems in this study. Increasing the percentage of recycled content (50%, 100%) in single-use bottles would lead to commensurate reductions in energy use and greenhouse gas emissions. Integral to increasing the use of rPET in single-use container production is recycling of containers after their useful life. Recycled containers serve as feedstock for rPET, and facilitate energy and GHG savings associated with a reduction in the production of virgin material. Further, in this study we observe recycling to reduce life-cycle solid waste by greater than **50%** for single-use systems as these containers are diverted from a landfill.

Minimizing distribution is another strategy with the potential to significantly reduce life-cycle impacts of single-use bottled water systems. We observed the distribution energy of a regional single-use bottled water increase by **360%** and **674%** if distribution is expanded to reach a national and international market respectively, contributing to a **45%** and **98%** increase in full life-cycle energy. Similar trends are seen in life-cycle greenhouse gas emissions.

Using biopolymer PLA for the single-use bottles stands to improve life-cycle energy and greenhouse gas profiles. In this study, PLA bottles led to a 10% decrease in container production energy relative to virgin-PET. While less of a reduction than observed by using 25% rPET, PLA still shows substantial life-cycle energy improvement. A **73%** reduction in greenhouse gas emissions relative to virgin-PET is a mainly function of plant specific CO_2 offsets in place at the Natureworks PLA facility in Nebraska. PLA's affect on life-cycle solid waste is a somewhat unclear. While PLA is touted as a 100% compostable polymer, it requires specialized facilities that create high-heat conditions. Natureworks reports that roughly 150 of such facilities exist in the US; however systems are not currently in place for the collection and transport of PLA to such facilities. As such, this study assumes that all PLA containers are sent to a landfill. If the PLA composting market continues to develop and reasonable means for a consumer to compost PLA exist, the life-cycle solid waste profile of a PLA bottled systems will show considerable improvement.

As with HOD systems, single-use systems bottling municipal water results in increased impacts in all categories, though particularly with regards to water use. Bottled municipal water offers no benefit over water served from a tap, and as such should be avoided to better leverage single-use systems against municipal tap systems with respect to life-cycle impacts.

6.2 Context of work

The results of this study were mostly consistent with expectations prior to completing the work. Due to the energy intensiveness of producing single-use plastic bottles, bottles systems were expected to perform the worst with regard to energy use and greenhouse gas emissions, as was observed. Further, HOD systems provided energy and GHG savings relative to single-use bottled systems, and municipal tap systems resulted in the most favorable environmental profile. Several of the outcomes of the study were somewhat unexpected. For example, we found that a nationally distributed bottled water (1500 distribution miles via truck) consumes more energy across the life-cycle than an overseas brand that arrives in the U.S. via an ocean freighter (4900 miles of ocean freighter). Despite the much longer distribution distance, the overseas water performs better with regard to energy use and GHG's due to the relative efficiency of ocean freight transport versus truck transport. Additionally, the dominance of residential dishwashing of the reusable drinking vessel was unexpected (32-46% of HOD systems and 89-94% of tap systems).

The results of this study are also in line with those of similar studies. Jungbluth *(2006)* found that tap water results in less than 1% of the environmental impact of unrefrigerated bottled water. While the comparative values from this study are somewhat higher than 1%, Jungbluth did not model the life-cycle of a reusable drinking vessel associated with consuming tap water, nor the residential dishwashing of this vessel. Van Hoof *(2002)* also found substantially lower energy, solid waste and emissions resulting from consumption of tap water relative to bottled – a result also observed in this study. Finally, like Gleick and Cooley *(2008)*, this study found the energy requirements of bottled water that is transported short distances (regionally) to be dominated by the energy used to produce the plastic bottles, while the energy used to transport water long distances is comparable to or even greater than that used to produce the bottles. While this finding is consistent with this study, Gleick's range of estimated energy requirement for producing bottled water was somewhat higher (5.6-10.2 MJ/l versus 4.4-8.8 MJ/l).

6.3 Implications

As stated in Chapter 1, the goal of this study is to assess dominant systems for the delivery of drinking water to a consumer household with respect to key life-cycle environmental impacts to determine the preferred systems for delivering drinking water. It is clear that from an environmental perspective, tap water systems are the preferred model for delivering drinking water to consumer households. With respect to HOD and particularly single-use bottled water, municipal tap systems provide considerable environmental advantage by minimizing energy use, greenhouse gas emissions and the generation of solid waste. The life-cycle water use profile of tap systems due to residential washing activities is an Achilles heel of these systems, but suggestion for improving performance in this regard have been made in **section 6.1** above. While HOD systems do outperform single-use systems by a substantial margin, relative to tap systems their toll on the environment with respect to energy, GHG's and solid waste renders them inferior.

This study was partly inspired by the current and growing backlash against bottled water (single-use) and its purported environmental impacts. The overarching goal of this study was to systematically quantify impacts of various drinking water systems, and recommend a course of action moving forward.

From an environmental perspective, it is easy to advocate the drinking of tap water as environmentally preferable and thus the right choice when it comes to drinking water. However, consumers have been led to believe that what is in the bottle is a superior product, and justifies the manufacturing of containers from non-renewable fossil based resources and distribution that sometimes reaches half-way around the world. This claim by water bottlers, that theirs is a superior product, has been challenged time and time again by groups like the National Resource Defense Council (NRDC), who based on a four year study completed in 1999, found major gaps in bottled water regulation and concluded that bottled water is not necessarily safer than tap water. More recently, a 2008 Environmental Working Group study revealed a surprising array of chemical contaminants in every bottled water brand analyzed. As such, the picture is less clear. Many cite convenience as the reason they prefer bottled water to tap; other cites taste. While consumer awareness of environmental issues is on the rise, and some reports show bottled water sales flagging to its lowest growth rate since 1991 *(Robinson-Jacobs, 2008)*, bottled water as a beverage category is soundly established and will not be going away anytime soon. Be that as it may, while I do advocate drinking tap water as the environmentally preferable and responsible choice, I also offer some suggestions for strategies aimed at reducing the impact of bottled water.

Bottled Water Bans:

A common principle in the environmental lexicon is that of the “3 R’s”, represent reduce, reuse and recycle as a strategy for reducing the environmental impact of goods and services. In line with this principle, bottled water bans would serve to reduce the production of single-use bottles for bottled water thereby reducing environmental impacts. I do not advocate a universal ban on bottled, which I believe would be not only impossible to administer but would interfere with appropriate uses of bottled water, of which there are several. Certainly in emergency situations, such as natural disasters, bottled water may be the only option for providing victims with drinking water. In this context, it is reasonable for aid organizations or governments to distribute bottled water.

A more reasonable approach to reduce the consumption of bottled water is the implementation of bans at the organizational level, for instance within city governments, universities even restaurants. This is a trend that has already begun and is currently on the rise. Increasing awareness of the environmental impacts of bottled water consumption has led to a growing list of U.S. mayors banning the purchase of bottled water with city funds including the mayors of Los Angeles, San Francisco, Salt Lake City, Chicago, Seattle and Toronto. This trend has recently moved beyond city governments. On May 5 2009, New York Governor David Patterson signed an executive order directing state agencies to phase out the purchase and use of bottle water at government workplaces. A growing list of U.S. colleges and universities has taken similar action, as have some high-end restaurants in cities like New York and San Francisco. This is certainly a beginning, and a trend that will hopefully continue into the future, possibly expanding into new areas such as public schools and retailer, particularly bulk retailer like Costco, Sam's Club and Wal-Mart.

Expanded Bottle-Bills:

Another strategy that has the potential to reduce the impact of the consumption of bottled water is the expansion of state bottle bills. Ideally, this would encompass states that do not have bottle bills implementing them, and those that do expanding them to cover non-carbonated bottled water. Currently 11 state have bottle bills that require consumers to place a deposit (5 or 10 cents) on the purchase of certain beverage container. These bills provide an incentive for container recycling, as consumer may recover their deposit by returning their bottles to the retailer. Increased recycling of beverage containers, particularly bottled water, has the potential to provide considerable environmental benefit by keeping bottles out of landfills and by reducing the need to extract raw materials from the earth and produce virgin material from which to manufacture new bottles, thereby reducing energy use. At present, estimates state that 86% of used water bottles end up in landfills *(Larson, 2007)*. Government funded studies conducted pre- and post- bottle bill show that the bills reduce litter by between **69% and 84%**. Further, the nation's 11 bottle bill states recycle **490 containers per capita per year** while the nation's 39 non-deposit states recycle **191 containers per capita per year**. This translates into recovery rates that are more than two and a half times higher in bottle bill states than states without bottle bills *(Gitlitz, 2003)*. As such, bottles bill have tremendous potential to improve the recovery rate of single-use water bottles.

To date, three states, Oregon, New York and Connecticut have updated their bottle bills to include bottled water (and other non-carbonated beverage containers) in 2009. Hopefully more will follow.

Education and Outreach:

Much of the problem with bottled water is related to consumer choice. Consumers appear to desire bottled water, and as long as that remains the case companies will capitalize on that desire by providing a bottled water product- simple supply and demand. While there is a contingent of consumers aware of the myriad environmental problems associated with the production and sales of bottled water, most are not. The most effective way to reduce the consumption of bottled water may be to increase consumer awareness through education and outreach campaigns. Currently there exist campaigns attempting to raise awareness of the trade-offs associated choosing bottled over tap water. These include Corporate Accountability International's "Think Outside the Bottle" and Food and Water Watch's "Tack Back the Tap", to name a few. While these campaigns have helped spark interest on college campuses, in city governments and amongst restaurateurs, efforts need to be undertaken to reach a wider more mainstream audience. City governments that have stopped purchasing bottled should make concerted efforts to publicize their decision, or take s step further with city sponsored campaigns urging the public to do the same. For example, since 1997, the city of Louisville, Kentucky has distributed more than 1.8 million refillable "pure tap" bottles to residents in efforts to change consumer behavior and encourage support for municipal tap systems *(Larson, 2007)*. Perhaps sympathetic city officials nationwide can initiate campaigns to target public schools. Recently, New York Governor David Patterson signed an executive order halting state-agency purchasing of bottled water. As the first Governor to take such action, Patterson is in a unique position to elevate the debate to a new level, and bring wider awareness to residents of New York and beyond.

6.4 Future Work

While this study provides a valuable assessment of the environmental impacts associated with various drinking water distribution systems, and contributes sound evidence to the burgeoning bottled versus tap water debate, there is still potential for future work on this topic.

Despite reports that state the opposite, many consumers still believe that bottled water is a superior product and feel compelled to drink bottled water out of concern for the safety of their tap water. Others cite bad taste as the reason they choose bottled over tap water. To improve both taste and purity, many consumers choose to install home reverse-osmosis systems onto their municipal taps. These systems include a variety of filter membranes, plastic filter casing, a pressurized water tank and various auxiliary plumbing connections. Also, as reverse-osmosis is an active process (the reverse of osmosis, a passive process that moves a solvent from an area of low solute concentration, through a membrane, to an area of high solute concentration), and thereby requires energy. A future life-cycle study of tap water systems could add another layer of depth by integrating the use of a home RO unit into the model. This would include modeling the life-cycle impact of the production and disposal of the RO unit, as well as the impacts of the unit's energy demands.

With regard to the modeling of single-use bottled water systems that employ PLA bottles as their primary container, a future study could add value by expanding the analysis involving PLA. For this study, I was unable to procure life-cycle data describing the composting of PLA. Further, composting PLA requires specialized facilities of which there are an estimated 150 in the United States. Due to this limited market, I assumed that composting of PLA is not a reasonable option for an average consumer at this time. As such I assumed PLA bottles were sent to a landfill. While the use of PLA in this study demonstrated the energy and greenhouse gas benefits of manufacturing bottles out of PLA, composting was not part of the analysis. Compostability, one of the most touted benefits of PLA, has the potential to significantly improve life-cycle solid waste profile of PLA bottles and should be part of future studies evaluated bottled water.

As the bottled water industry continues to come under fire for the impacts associated with their products, innovation in beverage containers will be explored as a way to minimize impacts. Currently, many bottled water companies are undertaking bottle light-weighting to reduce material use. Other companies are exploring altering the composition of bottles. Recently, ENSO Bottles, LLC, developed a form of a PET bottle that they claim will biodegradable within 1-5 years in microbial landfills, in either aerobic or anaerobic conditions *(Globe Net, 2009)*. There is, however, some debate as to whether the PET breaks down completely or merely degrades into a many small PET particles.

In response to recent sharp criticisms, bottled water will evolve with the use of new products and the employment of new practices. A future study of concerning the life-cycle impacts of drinking water delivery systems incorporating new products and practices in the bottled water industry would provide valuable insight into the response of the industry to external pressure and would serve to move the bottled versus tap debate forward.

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Appendix A

Material Composition of Systems

Single-Use Bottled Systems:

This system represents the delivery of drinking water in single-use 500 ml bottles packaged into 24 packs. In order to deliver 1000 gallons of drinking water to a consumer, this system requires **315.5** 24-packs of 500ml bottles, for a total of **7571** units of bottled water. The material composition of this system includes bottles, caps and the secondary packaging associated with 24-packs including a corrugated cardboard tray and stretch wrap. See Table A-1 for the material composition of single-use bottled systems by mass. Bottles caps and secondary packaging were weighed manually. The bottle and cap mass are the average of five products available on the market today. The mass of the bottle was assumed to be the same regardless of the material composition of the bottle (i.e. virgin-PET, rPET, PLA).

Table A-1

	Single-unit mass	**24-pack**	**Functional Unit**
	(g)	*(g)*	*(kg)*
500 ml bottle	15.6	374.4	118.1
Polypropylene Cap	2.1	50.4	15.9
Cardboard Tray	-	83.1	26.2
Stretch Warp	-	29.5	9.3
Drinking Water	500	12000	3785.4
Total:			**3954.9**

Note: water density assume 1 g/ml.

Home and Office Delivery Systems:

This system represents the delivery of drinking water in 5-gallon reusable jugs via a home and office delivery system (HOD). The water is consumed via a reusable drinking vessel (bottle or cup). In order to deliver the functional unit of 1000 gallons of drinking water, this systems requires the production of four polycarbonate jugs (50 reuses each) or eight PET jugs (25 reuses each). Regarding the reusable drinking vessel, this study assumed that 2 containers were required to deliver the full functional unit. The material composition of this system includes the 5-gallon jugs and the reusable drinking vessel including a polypropylene cap associated with the steel bottle. The cap associated with the 5-gallon jug was determined to represent less than 1% of the product systems by mass, and was excluded from this study. See **Table A-2** for the material composition of HOD systems by mass. The mass of a 5-gallon jug was assumed the same for polycarbonate and PET. All weights were determined manually.

Table A-2

	Single-unit mass	**Functional Unit**
	(kg)	*(kg)*
PC Jug	0.73	2.92
PET Jug	0.73	5.85
Stainless Steel Bottle	0.14	0.28
PP cap (steel bottle)	0.03	0.06
Glass Cup	0.31	0.62

Municipal Tap Water Systems:

This system represents the delivery of drinking water to a consumer household by way of a municipal tap water system. Drinking water is served in reusable drink vessel (bottle or cup). In consuming the functional unit of 1000 gallons of drinking water this study assumes that two reusable drinking vessels are needed. The material composition of the municipal tap water systems is composed solely of the reusable drinking vessel. See **Table A-3** for the material composition of municipal tap water systems by mass.

Table A-3

	Single-unit mass	**Functional Unit**
	(kg)	*(kg)*
Stainless Steel Bottle	0.14	0.28
PP cap (steel bottle)	0.03	0.06
Glass Cup	0.31	0.62

Appendix B

Production of Containers and Packaging

This appendix includes data for material production as well as fabrication of containers and packaging. In some cases, material production and fabrication are shown separately while in others the data is rolled together depending on the data source. The following processes are included in the appendix:

- Production of PET bottle/jug
- Production of Polypropylene (PP) cap
- Production of rPET bottle/jug
- Production of Polycarbonate (PC) jug
- Material production and fabrication of Polylactic Acid (PLA) bottle
- Production of Polyethylene (PE) wrap
- Production of corrugated cardboard tray
- Material production and fabrication of stainless steel bottle
- Production of glass kitchen cup

<u>Production of PET bottle/jug:</u>

PET (polyethylene terephthalate), is a thermoplastic polymer resin of the polyester family and consists of polymerized units of the monomer ethylene terephthalate. The raw materials to make PET are monoethylene glycol (MEG) and purified terephthalic acid (PTA) or dimethyl terephthalate (DMT) temperature and vacuum. The raw materials undergo a series of esterification processes followed by polymerization processes leading to the end product of amorphous PET. The amorphous PET then undergoes another polymerization step, solid state polymerization to produce bottle grade PET.

To fabricate bottles, bottle grade PET resin undergoes a blow molding process. Resin melted and molded into a hollow preform shape. The preform is then heated and introduced to increasingly high pressure air in order to blow the preform into shape of the terminal blow mold. The end result is a finished PET bottled. *(Bousted, 2005)*

Life-cycle data for the production of PET bottles from the extraction of raw materials through to the production of a finished PET bottle were obtained from the Association of Plastics Manufacturers of Europe (APME). **Table B-1** displays data regarding energy use, greenhouse gas emissions and production of solid waste associated with the production of PET bottles.

Table B-1: Production of PET bottles/jugs

Process:	*unit*	**Energy Use (MJ LHV)**	**GHG Emissions (kg CO_2 eq)**	**Solid Waste (kg)**
PET bottle production	*per kg*	103.9	4.4	0.0447

source: APME

Production of Polypropylene Caps:

Polypropylene is a thermoplastic polymer resin and consists of polymerized units of the monomer propylene. The polymer is formed via addition polymerization where many monomers bond together via rearrangement of bonds without the loss of any atom or molecule. This is in contrast to a condensation polymer which is formed by a condensation reaction where a molecule, usually water, is lost during the formation, such as the esterification process used to in the production of PET. The end result is polypropylene resin. To fabricate caps, PP resin undergoes an injection molding process. Melted resin is fed into a mold that is the reverse shape of the desired product. The melted plastic solidifies when it come into contact with the cooled wall of the mold. The mold opens and the finished part is ejected. *(Bousted, 2005)*

Life-cycle data for the production of PP caps from the extraction of raw materials through to the injection molding of PP resin into finished caps was generated by Franklin Associates, Ltd. was obtained from SimaPro 7.0 Life-Cycle Software. **Table B-2** displays data reflecting energy use, greenhouse gas emissions and production of solid waste associated with the production of PP caps.

Table B-2: Production of Polypropylene caps

Process:	*unit*	**Energy Use (MJ LHV)**	**GHG Emissions (kg CO_2 eq)**	**Solid Waste (kg)**
PP cap production	*per kg*	99.4	3.6	0.49

source: Franklin Associates, Ltd.

<u>Production of rPET Bottles/Jugs:</u>

The data described here represents the production of PET bottles from recycled PET bottles, and is based on a dataset developed by Franklin Associates, Ltd., for SimaPro 7.0 Life-Cycle Software. The Franklin dataset was adapted to include the burdens associated with collection and reprocessing of the recycled PET, due to the method of recycling allocation chosen for this study. The collection and reprocessing data for recycling PET is based on the Buwal 6.0 database in SimaPro 7.0. **Table B-3** displays life-cycle data reflecting energy use, greenhouse gas emissions and production of solid waste associated with the production of rPET bottles.

Table B-3: Production of rPET containers

Process:	*unit*	**Energy Use (MJ LHV)**	**GHG Emissions (kg CO_2 eq)**	**Solid Waste (kg)**
rPET bottle	*per kg*	46.1	2.56	0.39

source: Franklin Associates, Ltd.; Buwal 6.0

<u>Production of PC jug:</u>

Polycarbonate is a thermoplastic polymer that is commonly produced by reacting phosgene with bisphenol-A. To produce a hollow container, such as a jug, polycarbonate compound will undergo blow molding. Melted plastic is extruded into a hollow tube (a parison) and captured by closing it into a cooled metal mold. Low pressure air is blown into the parison, inflating it into the shape of the desired container. Once the plastic has cooled, the mold is opened and the container ejected. *(Bousted, 2005)*

This study uses data for the production of PC from the Association of Plastic Manufacturers of Europe (APME) and blow molding data from Ecoinvent. **Table B-4** displays life-cycle data reflecting energy use, greenhouse gas emissions and production of solid waste associated with the production of PC containers.

Table B-4: Production of PC jug

Process:	unit	Energy Use (MJ LHV)	GHG Emissions (kg CO_2 eq)	Solid Waste (kg)
Polycarbonate production	*per kg*	113	6.78	0.155
Blow molding	*per kg*	28.5	0.857	0.003
Total		141.5	7.64	0.158

source: APME; Ecoinvent

Production of PLA Bottle:

Polylactic acid (PLA) is a biopolymer derived from renewable resources, such as corn starch. Bacterial fermentation is used to produce lactic acid, which is then polymerized through a ring-opening polymerization process to form PLA *(Vink et al., 2003)*.

Data for the production of PLA is from Ecoinvent and is based on the production of PLA at the Natureworks plant in Nebraska. The data reflects CO_2 offsets through wind power certificates specific to the plant. To produce bottles from PLA, the resin undergoes a blow molding process as described with PET bottle production above. **Table B-5** displays life-cycle data reflecting energy use, greenhouse gas emissions and production of solid waste associated with the production of PLA bottles.

Table B-5: Production of PLA bottle

Process:	unit	Energy Use (MJ LHV)	GHG Emissions (kg CO_2 eq)	Solid Waste (kg)
PLA production	*per kg*	63.5	-0.0456	0.000
Blow molding	*per kg*	28.5	0.857	0.003
Total		92.0	0.81	0.003

source: Ecoinvent

Production of Polyethylene Wrap (LDPE):

Polyethylene is a thermoplastic polymer resin produced from the monomer ethylene. Low density polyethylene is a particular type of PE, with a relatively low density. LDPE is produced using a high pressure polymerization technology that is specific to LDPE. The end product is LDPE resin. To produce PE wrap from LDPE, the resin undergoes a film extrusion, a process in which the resin is melted and formed into a continuous profile. Molten plastic is gravity fed into the extruder, before heated further, forced into a die to form a tube. Air is used to inflate the tube, as it travels upwards, continually cooling and eventually passing through rollers that flatten the tube. The edges of the tube are split to produce two flat film sheets, and the film is wound onto reels. *(Bousted, 2005)*

Life-cycle data for the production of PE wrap from Ecoinvent are displayed in **Table B-6** and show energy use, greenhouse gas emissions and production of solid waste.

Table B-6: Production of PE wrap

Process:	*unit*	**Energy Use (MJ LHV)**	**GHG Emissions (kg CO_2 eq)**	**Solid Waste (kg)**
PE wrap production	*per kg*	92.6	2.36	0.0

source: Ecoinvent

Production of Corrugated Cardboard Tray:

Corrugated containers are fabricated from a “sandwich” of three primary paperboard components: outer liner, corrugating medium and inner liner. The liners are composed of unbleached Kraft paperboard, and the medium of semi-chemical paperboard. *(Franklin Associates)*

The data used for the production of corrugated board was developed by Franklin Associates, Ltd., and represents a typical U.S. average that contains 45% recycled content. This study assumes that the energy required to fold corrugated board into a trap is negligible relative to the production of the material and thus is not represented here. **Table B-7** displays life-cycle data for the production of corrugated cardboard with respect to energy use, greenhouse gas emissions and solid waste.

Table B-7: Production corrugated cardboard tray

Process:	*unit*	**Energy Use (MJ LHV)**	**GHG Emissions (kg CO_2 eq)**	**Solid Waste (kg)**
Tray Production	*per kg*	28.7	3.08	0.3

source: Franklin Associates, Ltd.

<u>Production of Reusable Stainless Steel Bottle:</u>

Stainless steel is a steel alloy that is defined by a minimum of 11% chromium by mass. Stainless steel is produced in an electric arc furnace where carbon electrodes contact recycled stainless scrap and various alloys of chromium (and nickel, molybdenum etc. depending on the stainless type). A current is passed through the electrode and the temperature increases to a point where the scrap and alloys melt. After some additional processing to finalize the exact desired chemistry, the material is hot rolled into its final form, a sheet of stainless steel. Some material receives cold rolling to further reduce the thickness as in sheets or drawn into smaller diameters as in rods and wire. *(Stainless Steel Information Center)*

Food grade stainless steel is typically 18/8 stainless steel, defined by 18% chromium, 8% nickel composition. Fabrication processes are used to transform 18/8 stainless steel from sheet form into a reusable water bottle. This study uses Ecoinvent data to represent life-cycle impacts associated with the production of 18/8 stainless steel and the processing required to fabricate a reusable water bottle. **Table B-8** displays data for the production of a stainless steel bottle with respect to energy use, greenhouse gas emissions and solid waste. While the dataset did not include values for life-cycle solid waste, this was deemed acceptable for this analysis due to the relatively small amount of stainless steel used to produced the two bottles used in the systems analyzed in this study.

Table B-8: Production of stainless steel bottle

Process:	*unit*	**Energy Use (MJ LHV)**	**GHG Emissions (kg CO_2 eq)**	**Solid Waste (kg)**
Stainlees steel production	*per kg*	87.6	5.1	0.0
Bottle fabrication	*per kg*	45.1	2.6	0.0
Total		132.7	7.7	0.0

source: Ecoinvent

<u>Production of a Glass Kitchen Cup:</u>

Glass is manufactured by melting high-purity sand with other minerals including limestone, soda ash (sodium carbonate), feldspar and post-consumer glass cullet. The mixture is melted, refined and fabricated into a finished product, typically in an integrated operation. A procedure similar to blow forming of plastics is used to fabricate the final container. Gobs of melted glass are dropped into a mold and blown with compressed air to form the glass into the shape of the mold. *(Franklin Associates)*

This study used life-cycle data developed by Franklin Associates, Ltd. for the production of glass containers to represent to fabrication of a generic glass kitchen cup. **Table B-9** displays data for the production of a glass container with respect to energy use, greenhouse gas emissions and solid waste.

Table B-9: Production of glass kitchen cup

Process:	*unit*	**Energy Use (MJ LHV)**	**GHG Emissions (kg CO_2 eq)**	**Solid Waste (kg)**
Glass Container Production	*per kg*	12.7	0.92	0.08

source: Franklin Associates, Ltd.

References:

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Appendix C

Life-Cycle Water Use

This appendix presents the data for used to determine life-cycle water use of the systems analyzed in this study. The data in this appendix refers to process related water use, and does not include the 1000 gallons drinking water that is common to all systems.

<u>Single-Use Bottled Systems:</u>

This study accounts for water use at three stages of the life-cycle of single-use bottled systems:

- Material production/fabrication of containers and packaging.
- Rinse water used in the bottling process.
- Wastewater from reverse-osmosis treatment during bottling operations (for municipally sourced water only.
- Water associated with power production.
- Water associated with transportation.

Material Production/Fabrication:

Water is consumed during the material production and fabrication of containers and packaging. **Table C-1** shows the data for water use by material.

Table C-1: Water use by material

Item	Unit	Water Use	source:
PET bottles	*ltr/kg*	3.5	*(a)*
Polypropylene (caps)	*ltr/kg*	2.2	*(a)*
Polyethylene wrap	*ltr/kg*	4.2	*(a)*
Corrugated board	*ltr/kg*	6.7	*(b)*

(a) APME, Eco-profiles of the European Plastics Industry
(b) BUWAL, Ecobalance of Packaging Materials

Bottling Process:

The bottling process represented in this study consumes water for rinsing of single-use bottles at a rate of **6.72%** of fill water *(McCormack, 2008)*. For 1000 gallons of fill water this amounts to **67.2 gallons.**

Reverse-Osmosis Treatment:

For those systems that use municipal water for bottling, the water will undergo reverse-osmosis treatment at the bottling plant. Reverse-osmosis typically recovers 75% of feed water *(McCormack, 2008)*, and thus produces 25% wastewater. As such, to produce 1000 gallons of treated drinking water, 1333.3 gallons of feed is required, and **333.3 gallons** is discharged as wastewater.

Power Production:

The production of power consumes water. Thermoelectric power plants consumptive (evaporative) water use is attributable to cooling processes. Evaporative water loss from the reservoir surfaces associated with hydroelectric plants also results in water being evaporated for electrical production. The national weighted average for thermoelectric and hydroelectric water use is 2.0 gal (7.6 L) of evaporated water per kWh of electricity consumed at the point of end use. (*NREL 2003*). For this study, **2.0 gallons** of water use is attributed to each kWh of energy consumed across all systems.

Transportation:

Fuels used for transportation (e.g. gasoline, diesel) require the consumption of water for their production. For this study we assumed **.15 gallon/mile** *(King, Webber 2008)* water consumption for all modes of transportation. While King and Webber purported this average value for light duty vehicles, a lack of additional data deemed this estimate acceptable for transportation in this study. Water use burdens were further scaled based on the mass of transported goods and capacity of transportation vehicles. While the King/Webber study was not full life-cycle based, a vehicle's life-cycle impacts are mostly attributed to the use phase (~90%) due to the combustion of fossil fuels *(Kasai, 2000)*.

Home and Office Delivery Systems:

This study accounts for water use at four stages of the life-cycle of HOD systems:

- Material production/fabrication of 5-gallon jugs.
- Rinse/wash water from the HOD bottling process.

- Wastewater from reverse-osmosis treatment during bottling operations (for municipally sourced water only.
- Water used during the residential dishwashing of the reusable drinking vessel.
- Water associated with power production.
- Water associated with transportation.

Material Production/Fabrication:

Water is consumed during the material production and fabrication of the reusable 5-gallon jugs. **Table C-2** shows the data for water use by material.

Table C-2: Water use by 5-gallon jug material

Item	Unit	Water Use	source:
PET jugs	*ltr/kg*	3.5	*(a)*
Polycarbonate	*ltr/kg*	4.0	*(a)*

(a) APME, Eco-profiles of the European Plastics Industry

HOD Bottling Process:

The HOD bottling process represented in this study consumes water for washing and rinsing of 5-gallons jugs at a rate of **1L per gallon of fill water** *(McCormack, 2008)*. For 1000 gallons of fill water this amounts to 2**64.2 gallons.**

Reverse-Osmosis Treatment:

See single-use bottled systems above.

Residential Dishwashing:

Water is consumed during the residential dishwashing of the reusable drinking container. Life-cycle water use depends on the number of dishwashing cycles run. Data for water used during residential dishwashing was obtained from the EPA's Energy Star website. The average Energy Star dishwasher consumes **4 gallons of water per cycle** *(EnergyStar.gov)*.

Power Production:

See single-use bottled systems above.

Transportation:

See single-use bottled systems above.

Municipal Tap Systems:

This study accounts for water use at during one life-cycle stage of municipal tap systems:

- Water used during the residential dishwashing of the reusable drinking vessel.
- Water associated with power production.
- Water associated with transportation.

Residential Dishwashing:

See HOD systems above.

Power Production:

See single-use bottled systems above.

Transportation:

See single-use bottled systems above.

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Appendix D

Municipal Water and Wastewater Treatment

This appendix presents the data for the municipal treatment and distribution of water to household tap systems as well as the treatment of wastewater at a municipal plant. The data reflects energy usage at the plant (for treatment and distribution to end-users in the case of water treatment) as well as the consumption of chemicals for treatment.

Municipal Water Treatment:

The data for the municipal treatment of water is applied to several parts of this study:

- Treatment of drinking water for the municipal tap systems.
- Treatment of single-use bottled or HOD drinking water that is sourced from municipal systems (prior to entering a bottling plant).
- Treatment of influent water for use in residential dishwashing of reusable container for municipal tap and HOD systems.
- Treatment of influent water used for rinsing/washing in the single-use and HOD bottling processes.

Utilities withdrawal fresh water from either groundwater or surface water sources, which they treat as necessary and distribute to customers. Depending on numerous factors including turbidity, microbial content and pH of the influent, the water can be treated with chemicals such as alum for coagulation, filtered through sand or membranes and disinfected with some form of a chlorine compound.

Energy

The primary data source for energy used during municipal water treatment is a survey of utilities across the U.S. completed as part of a study by the American Water Works Association. The study "Energy Index Development for Benchmarking Water and Wastewater Utilities" involved the development of a statistically representative sample of U.S. utility energy use and characteristics. Surveys were sent to utilities resulting in a final filtered data set of 122 water treatment plants. The utilities provided data concerning average daily flow as well as plant energy consumption including electricity and other fuels. A weighted average (by flow volume) of energy use was computed across all plants that included purchased electricity as well as natural gas used at the plant. Energy use is for plants operations as wells as subsequent distribution of water to end-users. **Table D-1** presents average estimated energy use at U.S municipal water treatment plants. Energy consumption by plant varied from .26 kWh/1000 gallons to 7.25 kWh/1000 gallons. The life-cycle impacts of plant energy use were determined with the use of SimaPro 7.0 Life-Cycle software.

Table D-1: Average Estimated Energy Use at U.S Municipal Water Treatment Plants

	Electricity Use	**Natural Gas Use**
	kwh	*therms*
per million gallons	1,629.88	41.63
per 1000 gallons	1.63	0.04163
per gallon	0.00163	4.163E-05

Source: AWWA

Chemicals

Water treatment plants use a variety of chemicals as part of the treatment process. Chlorine, chloramine or hypochlorite is commonly used for disinfection, sodium hydroxide for pH adjustment, alum or polymers for coagulation to name a few. Estimates for per gallon chemical use at a water treatment plant are based on usage and flow data from the Ann Arbor Water Treatment plant during a five year period from January 2000 through December 2005 *(Tripathi, 2007)*. While the data for Ann Arbor cannot be taken as representative of all plants in the U.S., this was the only dataset available for chemical use at a water treatment plant and was thus deemed acceptable for this study. **Table D-2** presents chemical usage at the Ann Arbor Water Treatment plant as used for analysis in this study. Life-cycle impacts associated with the production of these chemicals were determined with SimaPro 7.0 and are also presented I **Table D-2.**

Table D-2: Treatment Chemical Usage at Ann Arbor Water Treatment Plant

Treatment Chemical	lbs/gallon	Life-Cycle Impacts: Energy Use (MJ LHV)	GHG Emissions (kg CO_2 eq)	Solid Waste	source:
	(a)				
Lime	0.0016927	6.50	1.25	0.22	*(b)*
Sodium Hypochlorite	0.0000307	18.10	0.90	0.00	*(c)*
Carbon Dioxide	0.0001677	11.20	0.22	0.00	*(b)*
Oxygen	0.0000256	5.59	0.22	0.00	*(b)*
Sodium Hydroxide	0.0001331	19.70	1.15	0.07	*(b)*
Sodium Hexametaphosphate	0.0000091	206.00	12.70	0.94	*(d)*
Ammonia	0.0000087	35.80	2.28	0.01	*(d)*
Sodium Silico Fluoride	0.0000378	206.00	12.70	0.94	*(e)*

(a) Life-Cycle Energy and Emissions for Municipal Water and Wastewater Services. Tripathi, Malavika
(b) SimaPro 7.0 - BUWAL250, Eco-indicator 95
(c) SimaPro 7.0 - Ecoinvent, Eco-indicator 95
(c) SimaPro 7.0; NREL, 'Life-cycle Inventory of Biodiesel fuel and Petroleum Diesel fuel'.
(e) SimaPro 7.0 - Industry Data 2.0, APME, Eco-indicator 95

Municipal Wastewater Treatment:

The data for the municipal wastewater treatment is applied to several parts of this study:

- Treatment of effluent water from single-use and HOD bottling operations used for bottle rinsing/washing.
- Treatment of effluent water from residential dishwashing of reusable container for municipal tap and HOD systems.

Wastewater from industries and most households flows to a local wastewater treatment plant where pollutant levels are reduced before discharge to the environment. Wastewater is treated in stages involving various treatment technologies. The specific treatment type and level depends on the plant as well as the quality of the influent.

Primary treatment of wastewater involves straining of the influent to remove all large objects. Next, the water is routed into a large tank where gravity settling takes place. Solids sink to the bottom while oil and grease rise to the top and are skimmed off the surface.

Secondary treatment is meant to substantially degrade the biological content of the wastewater through the use of microorganism and other methods including activated sludge, trickling filtration, rotating biological contactors and lagoons and oxidation ponds.

Advanced or **Tertiary treatment** is the final stage of wastewater treatment and serves to raise the effluent quality before it is discharged into the receiving environment. This stage often includes additional filtration, nutrient removal and a final disinfection step. *(Metcalf & Eddy, 2004)*

Energy

As with the water treatment, the primary data source for energy used during the wastewater treatment process is a survey of utilities across the U.S. completed as part of a study by the American Water Works Association - "Energy Index Development for Benchmarking Water and Wastewater Utilities". Surveys were sent to utilities resulting in a final filtered data set of **243** wastewater treatment plants. The utilities provided data concerning average daily flow as well as plant energy consumption including electricity and other fuels.

A weighted average (by flow volume) of energy use was computed for all plants that included purchased electricity, natural gas and fuel oil used at the plant. Because the water from washing drinking containers and rinsing bottles is not expected to contribute bio-solids to the wastewater treatment process, the energy reported below has been scaled down. According to "Wastewater Engineering; Treatment, Disposal and Reuse" *(Metcalf & Eddy, 2004)* approximately 56% of all energy use in a typical wastewater treatment plant is associated with the treatment of bio-solids through the activated sludge process. This energy has been removed since bio-solids will not be produced by the systems in this study. **Table D-3** presents average estimated energy use at U.S municipal water treatment plants. The life-cycle impacts of plant energy use were determined with the use of SimaPro 7.0 Life-Cycle software.

Table D-3: Average Est. Energy Use at U.S Municipal Wastewater Treatment Plants

	Electricity Use	Natural Gas Use	Fuel Oil Use
	kwh	*therms*	*gallons*
per million gallons	1,640.69	17.10	0.7222
per 1000 gallons	1.64	0.02	0.0007
per gallon	0.0016	1.7E-05	7.2E-07

Source: AWWA

Chemicals

Wastewater treatment plants use a wide range of chemicals as part of the treatment process depending on the level of treatment desired and the characteristics of the influent. For this study, the estimate of chemical usage is based on data reported for three wastewater treatment plants, Ann Arbor, MI, Ypsilanti, MI and Laguna, CA. While these three utilities cannot be assumed as representative of all plants across the U.S., the energy for chemical production accounts for ~10% of the life-cycle energy use at all three utilities. Because it represents such a small portion of total wastewater treatment energy, an estimate of this type was deemed acceptable. **Table D-4** presents average chemical usage across three wastewater treatment plants as used for analysis in this study. Life-cycle impacts associated with the production of these chemicals were determine with SimaPro 7.0 and are also presented I **Table D-4.**

Table D-4: Chemical Usage at U.S Municipal Wastewater Treatment Plants

Treatment Chemical	lbs/gallon	Life-Cycle Impacts: Energy Use (MJ LHV)	GHG Emissions (kg CO_2 eq)	Solid Waste (kg)	*source:*
	(a)				
Lime	0.000309	6.50	1.25	0.22	*(b)*
Ferric Chloride	0.000112	17.60	0.85	0.00	*(c)*
Ferrous Chloride	0.000064	17.60	0.85	0.00	*(c)*
Hypochlorite	0.000014	18.10	0.90	0.00	*(c)*
Alum	0.000017	6.29	0.27	0.00	*(b)*

(a) Life-Cycle Energy and Emissions for Municipal Water and Wastewater Services. Tripathi, Malavi
(b) SimaPro 7.0 - BUWAL250, Eco-indicator 95
(c) SimaPro 7.0 - Ecoinvent, Eco-indicator 95

References

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Appendix E

Water Bottling Operations

This appendix describes the data used to represent operations at a bottling plant, including bottling for single-use bottled systems and home and office delivery systems. Bottling operations include the activities of purifying the water and filling the bottles, and in the case of the single-use bottled systems, packaging the bottles into 24-packs.

<u>Treatment Processes:</u>

This analysis includes the bottling of water acquired from municipal sources as well as that acquired directly from natural sources such as a spring. Water acquired from municipal sources will undergo filtration followed by reverse osmosis, UV disinfection and ozone treatment prior to being used to fill bottles. With spring water, bottlers normally forego the reverse osmosis step *(McCormack, 2008))*.

Filtration:

The purpose of filtration is to remove physical particles from the water. Filtration is a physical process that employs various media including screens, membranes or granular materials *(Senior, Dege, 2005)*.

Reverse-Osmosis:

Reverse-osmosis is a diffusion controlled membrane process that is effective at removing organic matter from water. It works by using pressure to force a solution through a membrane, retaining the solute on one side and allowing the pure solvent to pass to the other side. A typical reverse-osmosis process requires a pump, membranes in a housing element, control valves and sensors (including pressure gauges and flow meters) *(Senior, Dege, 2005)*.

Ultraviolet Disinfection:

UV irradiation is an antimicrobial treatment method that disinfects water by degrading the nucleic acid in bacterial cells. Most UV disinfection units have a tubular arrangement that pass water by a perpendicularly mounted mercury discharge lamp *(Senior, Dege, 2005)*.

Ozone Treatment:

Ozone treatment is a chemical oxidation process that uses ozone to oxidize reduced organic species in order to destroy compounds that can cause undesirable tastes and odors. In particular, ozone treatment is widely used in the bottled water industry to remove dissolved iron or manganese *(Senior, Dege, 2005)*.

Single-Use Bottling:

Data for the energy demands of bottling for single-use bottled systems was obtained from Norland International, Inc., provider of turnkey technology solutions for the bottled water industry. Norland International designs and manufactures a variety of complete bottling lines. Technical specifications including power requirements for a small bottling line (500ml-1L bottles) were provided by Norland. The bottling line consists of the water treatment technology, bottle rinser/filler/capper/labeler and conveyor systems that move the bottled water through various other packaging activities. The final product is 24-packs of 500ml bottled water packaged in cardboard track and wrapped in PE shrink wrap. The process of rinsing bottles generates wastewater at a rate of 6.7% of fill. As such, included in the single-use bottling results is the municipal water treatment of the influent water used for rinsing and the municipal wastewater treatment of the effluent. The water/wastewater treatment energy requirements are not included in this appendix, but are described in Appendix D. Power requirements for the small bottling line used for this study are shown in **Table E-1** below.

Home and Office Delivery Bottling:

Data for the energy demands of bottling for HOD systems was obtained from Norland International, Inc. Technical specifications including power requirements for a large bottling line (3-5 gallon jugs) were provided by Norland. The bottling line consists of the water treatment technology followed by a bottle washing/filling unit. The washing, which allows the 5-gallon jugs to be reused multiple times, involves a pre-rinse, a wash with 140F water, and a final rinse. The washing/rinsing process generates 1 liter of wastewater per 1 gallon of fill water. As such, included in the HOD bottling results is the municipal water treatment of the influent water used for washing/rinsing and the municipal wastewater treatment of the effluent. The water/wastewater treatment energy requirements are not included in this appendix, but are described in Appendix D. Power requirements for the large bottling line used for this study are shown in **Table E-2** below. Also included in the data used to estimate HOD bottling energy use is the energy (heat from natural gas) required to heat the water for washing, shown in **Table E-3**.

Table E-1: Small Bottling Line Power/Energy Requirements

Small Bottling Operation - 500ml:

Norland International System capable of filling/labelling/packaging 4500 bottles/hour.

Functional Unit of 1000 gallons (7571 bottles) = **1.68** hours of operation.

	System Component	KW/Hr	KWh/1000 gallons
Pre-Treatment	Carbon Filter	0.1	0.17
	Water Softener	0.1	0.17
	UV System	0.6	1.01
	RO System (10,000 gpd)[1]	5.0	12.00
	Ozone System	6.1	10.26
Filling & Packing	Bottle Rinser	0.3	0.50
	Bottle Filler	2.6	4.37
	Labeler/Capper	1.0	1.68
	Cincher	1.9	3.20
	Conveyor System (36')	0.4	0.67
	Bottle Unscrambler	2.3	3.87
	Date Coder	0.2	0.34
	Conveyor System (14')	0.4	0.67
	Case Packer 5000	0.8	1.35
	Shrink Pack 5000	16.0	26.92
	Total for 1000 Gallons:		
	Municipal Source[2]:		67.18
	Spring/Well Source[2]:		55.18

Source: *Norland International, Inc., SP5000 system.*

Notes: *[1] For 10,000 gpd, 8 hour work day, RO unit runs 24 hours.*

[2]Water sourced from municipal supplies require RO treatment while Spring/Well water does not.

Table E-2: Large Bottling Line Power/Energy Requirements

Large Bottling Operation (5-gallon jugs for Home and Office Delivery)

Norland International System capable of washing/filling 160 bottles/hour.

Functional Unit of 1000 gallons (200 jugs) = **1.25** hours of operation.

	System Component	KW/Hr	KWh/1000 gallons
Pre-Treatment	Carbon Filter	0.1	0.13
	Water Softener	0.1	0.13
	UV System	0.6	0.75
	RO System (10,000 gpd)[1]	5.0	12.00
	Ozone System	6.1	7.63
	Bottle washer/filler	44.0	55.00
	Total For 1000 Gallons[2]		
	Municipal Source[3]:		75.63
	Spring/Well Source[3]:		63.63

Source: Norland International, Inc., Triton 450.

Notes: [1] For 10,000 gpd, 8 hour work day, RO unit runs 24 hours.

[2]Does not include energy requirement for heating water to 140F.

[3]Water sourced from municipal supplies require RO treatment while Spring/Well water does not.

Table E-3: Water Heating Energy Use for HOD Bottling

Specific Heat of Water:		
(J/ml*K)	4.184	*(a)*
Quantity of Water:		
(ml)	500,000	*(b)*
Temperature change:		
(deg C)	47	*(c)*
Energy Required:		
(joules)	98,324,000	*(d)*
(BTU)	**93,139.17**	

(a) http://chemed.chem.purdue.edu/genchem/topicreview/bp/ch5/heat.html

(b)1L waste/1 Gal fill = 1000 L waste. Assumed 1/2 used for washing, 1/2 for pre-rinse/rin

(c) Room temperature water assumed 13C. 13C to 60C(140F)= 47C change.

(d)Energy required = specific heat x volume x temperature change

References:

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Appendix F

Residential Dishwashing

This appendix describes the residential dishwashing activities associated with the reusable drinking vessel used in the HOD and municipal tap systems in this study. In both the HOD and municipal tap system, drinking water is served in a reusable drinking vessel (stainless steel bottle or glass cup) that is periodically washed in a residential dishwasher. The baseline scenario used in this study assumes:

- The reusable container is washed after every 4 uses.
- On average, a residential dishwasher is filled with 30 items. The reusable drinking vessel being one of these items represents 3.33% of the load. As such, **3.33%** of the burdens associated with a dishwashing cycle are assigned to the washing of the reusable container.

This study uses two distinct reusable drinking vessels across the variants analyzed on this study: a 12 oz. glass kitchen cup and an 18 oz. stainless steel bottle. For either of the reusable containers, the study assumes it is washed after every four uses. As such, more water is consumed with the 18 oz. bottle between washes, and more washing cycles are required for the 12 oz. cup. **Table F-1** shows the number of dishwashing cycles required to serve the full functional unit of 1000 gallons of drinking water for both reusable containers.

Table F-1: Number of Dishwashing Cycles Required for Functional Unit

	4-uses/wash
12 oz. glass cup	2,667
18 oz. stainless steel bottle	1,778

Note: 1000 gallons = 128,000 oz.

Data for the energy and water requirements of residential dishwashing were obtained from the U.S EPA's Energy Star website. Energy consumption was calculated by taking the average of 688 active Energy Star residential dishwashers. **Table F-2** displays the average energy and water burdens associated with residential dishwashing.

Table F-2: Average Environmental Burdens from Residential Dishwashing

kWh/cycle:	1.39
Avg. H_2O/cycle, gal:	4

source: EnergyStar

Table F-3 displays the life-cycle energy and water use burdens associated with each of the reusable drinking vessels as evaluated in this study at 3% of each dishwashing cycle.

Table F-3: Energy and Water Use by Reusable Container Type

12 oz. glass cup	
kWh used:	111.40
water used:	320
18 oz. stainless steel bottle	
kWh used:	74.26
water used:	213.33

Appendix G

Transportation

This appendix describes the data used in this study for transportation/distribution at various stages of the life-cycle system. Included are data for transportation via:

- Single-unit diesel truck
- Diesel tractor-trailer
- Passenger car
- Delivery van
- Diesel Locomotive
- Ocean Freighter

Single-Unit Diesel Truck:

The single-unit diesel truck is used in this study for the distribution of single-use-bottled water **of less than 100 miles** including transportation from a bottler to a regional distributor and from a distributor to a retail store. This study assumes that a single-unit truck (versus a tractor-trailer) is used for short distance freight trucking (<100 miles). Data for transportation via a single-unit diesel truck from Franklin Associates is shown in **Table G-1.**

Table G-1: Single-Unit Diesel Truck Transport

unit	Energy (MJ LHV)	GHG's (kg CO2 eq)	Solid waste (kg)
per tkm	2.88	0.209	0.00109

Source: Franklin Associates, Ltd.

Diesel Tractor-Trailer:

The diesel tractor-trailer truck is used in this study for road transportation distances of **greater than 100 miles** including the distribution of single-use bottled water in *variants 5 and 7*. This study assumes that a diesel tractor-trailer (versus a single-unit truck) is used for long-distance freight trucking (>100 miles; 1500 miles in this study).). Data for transportation via a diesel tractor-trailer from Franklin Associates is shown in **Table G-2.**

Table G-2: Diesel Tractor-Trailer Transport

unit	Energy (MJ LHV)	(kg CO2 eq)	Solid waste (kg)
per tkm	1.02	0.0744	0.000388

Source: Franklin Associates, Ltd.

Passenger Car:

The passenger car is used in this study for the transport of bottled water from a retail store to a consumer household. This study assumes that each 24-pack of bottled water consumed is purchased at a retail store as one of thirty items purchased, and thus receives 3.33% of the burdens of transport for each trip to the store. Each 24-pack of bottled water is allocated one retail trip. Burdens for retail transport are based on distance rather than weight, as it was assumed that the weight of an average load of groceries will not substantially affect the fuel consumption of the vehicle. The average roundtrip distance to a retail store in the U.S. is **8 km** *(Sivaraman, 2007)*. Data for transportation via a passenger vehicle are shown in **Table G-3.**

Table G-3: Passenger Car Transport

unit	Energy (MJ LHV)	(kg CO2 eq)	Solid waste (kg)
per km	0.00292	0.000227	1.12E-08

Source: Delft Technical University, Netherlands, IDEMAT 2001 database

Delivery Van:

The delivery van is used in this study for the delivery of HOD bottled water, and the pickup of empty 5-gallon jugs after the consumption of the drinking water. The study employs one-way transportation distance of 10/20 miles as part of a HOD delivery route, depending on the variant. Burdens are calculated by weight and consist of the weight of jugs and water on delivery, and the weight of empty jugs on the return trip.   Data for transportation via a delivery van are shown in **Table G-4.**

Table G-4: Delivery Van Transport

unit	Energy (MJ LHV)	(kg CO_2 eq)	Solid waste (kg)
per tkm	7.38	0.553	0

Source: BUWAL 6.0

Diesel Locomotive:

The diesel locomotive is used in this study for the transport of overseas single-use bottled water from the bottling plant to a sea port. This model is roughly based on transportation logistics used by Evian ™, which includes ~300 miles of rail travel from Évian-les-Bains, France to the Port of Marseilles (where it bottled water is ultimately loaded onto an ocean freighter and shipped). Data for rail transport using a diesel locomotive are shown in **Table G-5**.

Table G-5: Diesel Locomotive Transport

unit	Energy (MJ LHV)	GHG's (kg CO_2	Solid waste (kg)
per tkm	0.261	0.0191	0.0000992

Source: Franklin Associates, Ltd.

Ocean Freighter:

The ocean freighter is used in this study for the transport of overseas single-use bottled water from the Port of Marseilles, France to the Port of New York, ~4500 miles. Data for ocean freighter transport are shown in **Table G-6.**

Table G-6: Ocean Freighter Transport

unit	Energy (MJ LHV)	GHG's (kg CO2	Solid waste (kg)
per tkm	0.224	0.0166	0.0000847

Source: Franklin Associates, Ltd.

Appendix H

End-of-Life Disposition

This appendix describes the data used for end-of-life disposition of containers and packaging including single-use bottles and caps, secondary packaging, HOD 5-gallon jugs and the reusable drinking vessel. In this study, materials are either sent to a land fill or are recycled at the end of their useful life. It is assumed that PP caps and all secondary packaging are sent to a land fill regardless of the variant at issue, while single-use and HOD containers are either recycled or land filled. Reusable drinking vessels (stainless steel bottle, glass cup) are recycled (steel bottle) or landfilled (glass cup).

Land Filling:

The land filling model used in this study is based on data derived from Swiss systems for waste disposal in a landfill. The inventory data for land filling is based on the average composition of materials (PET, PP etc.) in municipal waste in Switzerland, with material specific transfer coefficients. The data includes waste collection, waste water treatment, sludge treatment, sludge incineration and energy recovery from landfill methane gas. With regards to PLA, theoretically a PLA bottle degrading in a landfill would release CO_2/methane; the temperature inside of modern sanitary landfills, however, is likely too low for biodegradation (and subsequent CO_2/methane releases). As such, I assumed no PLA biodegradation occurs in the land fill.

Data for the land filling of various materials are shown in **Table H-1** below.

Table H-1: Land Filling of Various Materials

per kg material	**Energy (MJ LHV)**	**GHG's (kg CO2 eq)**	
Polyethylene Teraphthalate	0.198	0.194	
Polycarbonate	0.198	0.194	*(a)*
Polylactic acid	0.198	0.194	*(a)*
Polyethylene	0.204	0.288	
Polypropylene	0.201	0.244	
Glass	0.193	0.014	
Corrugated Cardboard	0.343	0.0195	

Source: BUWAL (Swiss Agency for Environment, Forests and Landscapes

(a) Data for PC and PLA was not available, assumed same as PET.

Recycling:

The approach to recycling used in this analysis is to assign full burdens for virgin material production and end-of-life disposal to the product system for which they occur. As such, all burdens for virgin material production and initial product fabrication are assigned to the first product system using the material. The first system bears no disposal burdens for any material that is recovered and recycled for use in a second product system. Postconsumer material recovered from the first system comes into the second system free of its virgin material burdens. The system using the postconsumer material (rPET bottles/jugs) bears the full burdens of collecting and reprocessing the material for use in the second product system, as well as well as the full burdens for the second product fabrication and use. The system using the postconsumer recycled material also bears the full burdens for disposal of the material at the end of life. Burdens associated with the recycling of PET are accounted for in the data for the production of rPET bottles as described in **Appendix B**.

Appendix I

Sensitivity Analyses

This appendix contains sensitivity analyses conducted on key model inputs to ascertain their overall impact on the life-cycle modeling results. Sensitivities were conducted on life-cycle energy only. Included are sensitivity analyses of:

- The percentage of dishwashing burdens allocated to the reusable containers in the municipal tap systems.
- The frequency of washing of reusable containers in the municipal tap systems.
- The percentage of recycled content in the single-use bottled water systems.
- The number of reusable containers required to deliver the full life-cycle of drinking water.
- Running the tap before filling a reusable container with municipal tap water.

Percentage of Dishwashing Burdens:

The baseline scenario of this study assumes that a residential dishwasher is filled, on average, with 30 items. Representing 1 out of 30 items, the washing of a reusable drinking vessel is allocated 3.33% of the dishwashing burdens. To determine the impact of this assumption, a sensitivity analysis was conducted to evaluate the burdens associated with a lower (more items) and higher (fewer items) allocation of the dishwashing burdens to the reusable container. As such, results were calculated using both a **2%** and **4%** allocation of dishwashing burdens. The sensitivity was conducted with regard to the use of the reusable stainless steel bottle used in the municipal tap system. Results are displayed in **Table I-1** below:

Table I-1: Sensitivity on Dishwashing Allocation

		MJ	
	Baseline (3.33%)	**Low (2%)**	**High (4%)**
Dishwashing Burdens:	933.3	622.3	1244.6
% change from baseline	-	33.3%	33.4%
Total Life-Cycle Energy:	1052.9	741.7	1364.2
% change from baseline		29.6%	29.6%

As shown in **Table I-1** the allocation of dishwashing burdens to the reusable container has considerable impact on total life-cycle energy. A reduced allocation leads to a **33.3%** reduction in dishwashing burdens, and a **29.6%** reduction in total life-cycle energy. By allocating more of the dishwashing burdens to the reusable container, energy use increases by **33.4%** and total life-cycle energy by **29.6%.** This demonstrates that the life-cycle performance of a municipal tap system can be substantially improved by minimizing the burdens associated with dishwashing. This can be accomplished by only running the dishwasher when it is fully loaded.

Frequency of Washing:

The baseline scenario of this study assumes that the reusable drinking vessel is washed after every four uses. While this may be a sound assumption for some, many will opt to wash their container more frequently. To test the impact of this assumption, a sensitivity analysis was conducted to determine the impact of more frequent washing of the reusable drinking container. Impacts on life-cycle energy use were calculated for the municipal tap systems utilizing a stainless steel drinking vessel when the vessel is assumed to be washed **after each use** and **after every other use**. Results are displayed in **Table I-2** below:

Table I-2: Sensitivity on Frequency of Residential Washing

	MJ		
	Baseline (every 4 uses)	**Every 2 uses**	**After each use**
Dishwashing Burdens:	933.3	1866.7	3733.3
% change from baseline	-	100.0%	300.0%
Total Life-Cycle Energy:	1052.9	1986.7	3853.0
% change from baseline		88.7%	265.9%

As shown in **Table I-2** the frequency of washing of the reusable container has considerable impact on total life-cycle energy of municipal tap systems. Increasing the washing frequency from the baseline of every four uses to every two uses increases dishwashing energy use by 100% (933.3 MJ to 1866.7 MJ). Washing the reusable container after every use, increases energy use by 300% to 3733.3 MJ. With respect to total life-cycle energy, increasing washing frequency to every two uses leads to an increase in energy use of 88.7%; washing after each use increases life-cycle energy use by 265.9%. Clearly, frequency of washing of the reusable drinking vessel is a key factor in the life-cycle of municipal tap water systems. To reduce life-cycle energy use of municipal tap water systems, the frequency of washing of reusable drinking vessels should be minimized.

The Number of Reusable Containers:

The baseline scenario of this study assumes the use of a single reusable container to deliver the full 1000 gallons of drinking water to a consumer. While this is a reasonable assumption, it is possible that some consumers/households would employ several reusable containers over the time period required to consume 1000 gallons of drinking water. To determine the impact of using more than one reusable container, a sensitivity analysis was conducted to evaluate the associated burdens with regard to life-cycle energy. Results were calculated for the use of **two** and **four** reusable containers with regard to the use of the stainless steel bottle used in the municipal tap systems. Results are displayed in **Table I-3** below:

Table I-3: Sensitivity on Number of Reusable Containers

	MJ		
	Baseline (1 container)	**Medium (2)**	**High (4)**
Container Life-Cycle Energy	43.3	86.5	173.0
% change from baseline	-	100.0%	300.0%
Total Life-Cycle Energy:	1052.9	1096.2	1182.7
% change from baseline		4.1%	12.3%

As shown in **Table I-3** the additional of more reusable containers to the model has a relatively minimal impact on overall life-cycle energy. The additional of a second container increases life-cycle energy by **4.1%**, while the additional of three containers (total of four) raises energy by **12.3%**. The additional of more reusable containers does not significantly affect life-cycle performance of the municipal tap systems with respect the HOD and single-use bottled systems.

Running the Tap Before Filling a Reusable Container with Municipal Tap Water:

The baseline scenario for the municipal tap system evaluated in this study assumes the consumption of precisely 1000 gallons of water to provide a consumer with 1000 gallons of drinking water. In other words, no water is wasted in the provision of drinking water. For purposes of this study, this assumption was deemed acceptable. It is possible, however, that a consumer might run the tap before filling a reusable container with water due to behavioral preferences (i.e. to clear standing water from the pipes; to wait for colder water; to rinse the container, etc.). A sensitivity analysis was conducted to determine the energy impact of running the water before the filling of the reusable container with drinking water.

Results were computed for the consumption of 1500 and 2000 gallons of municipal tap water and are presented in **Table I-4** below:

Table I-4: Energy Impact of Consuming Additional Tap Water

	mmBTU		
	Baseline (1000 gallons)	**Medium (1500 gallons)**	**High (2000 gallons)**
Municipal Treatment Energy	76.0	115.0	153.0
% change from baseline	-	51.4%	101.4%
Total Life-Cycle Energy:	1052.9	1090.9	1130.0
% change from baseline		3.6%	7.3%

As shown in **Table I-4**, the consumption of water in excess of the 1000 gallons of drinking water has a relatively small impact on total life-cycle energy. The medium scenario (consumption of 1500 gallons to provide 1000 gallons of drinking water) leads to a 3.6% increase in life-cycle energy, while the high scenario (consumption of 2000 gallons) leads to a 7.3% increase. The life-cycle of the municipal tap systems is dominated by the residential washing of the reusable container (>88% of total life-cycle energy). As such, increasing water use does not lead to significantly different results.

Percentage of Recycled Content in the Single-Use Bottled Water Systems:

The baseline scenario for single-use bottled systems that employ recycled content (rPET) in the bottles is 25% rPET. As shown in **Chapter 2,** the inclusion of recycled content in single-use bottles reduces life-cycle energy, solid waste and greenhouse gas burdens. Currently, the use of recycled content in the bottled water industry is not a standard practice. Mountain Valley Spring Water, one of the few bottled water companies to use recycled content in their products, recently made a public commitment to using 25% recycled content in all of their PET containers with the goal of moving towards 50% rPET over the next year. Here, a sensitivity analysis is conducted to demonstrate the benefits of using additional amounts of recycled content in single-use bottled systems. Results were calculated for 50% and 100% recycled content for regional single-use bottled systems that employ recycling after the useful life of the container with respect to life-cycle energy. Results are shown in **Table I-5** below:

Table I-5: Life-Cycle Energy Benefits of Increased Recycled Content:

	MJ			
	Virgin PET	**25% rPET**	**50% rPET**	**100% rPET**
Container Production Energy	13857.2	11940.8	10445.1	7068.9
% reduction from virgin	-	14%	25%	49%
Total Life-Cycle Energy	18601.7	16661.0	15165.4	11742.8
% reduction from virgin	-	10%	18%	37%

As shown in Table I-5, the percentage of recycled content included in the single-use bottle has a significant impact on both container production energy and total life-cycle energy. Relative to the use of Virgin-PET single-use bottles, the use of 25%, 50% and 100% rPET leads to a 14%, 25% and 49% reduction in container production energy. These reductions translate into 10%, 18% and 37% reductions in total life-cycle energy. Incorporating increasing amounts of rPET into bottles stands to substantially improve the life-cycle energy profile of single-use bottled systems. Commensurate benefits can be expected in life-cycle solid waste and greenhouse gases.

Appendix J

Glossary

GHG: greenhouse gas

HDPE: High-density polyethylene plastic

HOD: Home and office delivery water system

Kg CO_2eq: Kilogram of carbon dioxide equivalents; a measure of global warming impact based on a gas's global warming potential relative to carbon dioxide.

LCA: Life-cycle assessment; a systematic method for quantifying a product/system's environmental impact across its entire life-cycle, from extraction of raw materials to disposal.

LCI: Life-cycle inventory

LCIA: Life-cycle impact assessment

LDPE: Low-density polyethylene plastic

LLDPE: Linear low-density polyethylene plastic

MJ: Mega joule (energy value)

MJ LHV: Mega joule lower heating value; The lower heating value of a fuel is defined as the amount of heat released by combusting a specified quantity and returning the temperature of the combustion products to 150 °C. LHV assumes all the water component is in vapor state at the end of combustion (in product of combustion), as opposed to HHV that assumes all the water component in liquid form of the combustion gas.

MmBTU: One million BTU (British thermal unit; energy value)

PC: Polycarbonate plastic

PE: Polyethylene plastic

PET: Polyethylene terephthalate plastic

PP: Polypropylene plastic

Quad: An energy unit equivalent to a quadrillion BTUs

RO: Reverse osmosis; a treatment technology used to produce drinking water

rPET: PET made with recycled content

UV: Ultraviolet treatment; a disinfectant treatment technology used in the production of bottled water

Virgin PET: PET made with virgin content