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Life Cycle and Cost Assessments of Atmospheric Water Generation Technologies and Alternative Potable Water Emergency Response Options

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ABSTRACT

There are several ways to provide potable water to the community in times of an emergency. In recent disaster events, bottled water has generally been provided to the affected population. However, some new products have come on the market that can generate water from the atmosphere and may be an effective alternative to bottled water in times of emergencies. These products are known as atmospheric water generators (AWGs). This research uses life cycle assessment (LCA) to evaluate the potential environmental impacts associated with the bottled water system and the AWG system based on a suite of environmental indicators. A companion cost analysis is also conducted using net present value calculations. The project evaluates bottled water systems associated with a single-serve 16.9 oz bottle served in 24 pack cases and multi-serve 5-gallon reusable jugs, in addition to two brands of AWGs designed to operate at multiple scales, manufactured by Watergen and Ecoloblue, respectively. Life cycle inventory data were collected from vendor-provided data and published peer reviewed literature to be modeled in openLCA v1.7.0. Several sensitivity analyses were conducted to quantify the effect on results of single-serve bottle weights, transportation distance in delivering multi-serve jugs, source of water for filling the bottles, recycled content and recycling allocation methods in bottled water systems, electrical grid mixes for AWGs, volume of water produced by AWGs and the method used to wash the reusable container for drinking water either from the multi-serve jug or the AWGs. Results indicate that the AWGs typically have higher impacts across all environmental impact categories as compared to the bottled water systems. The multi-serve reusable jug has the lowest impacts across the environmental impact categories of all the systems studied. The impacts of the multi-serve jug can be further reduced by lowering the transportation distance to and from the user. The operational life cycle stage of the AWGs has the highest impacts across all impact categories due to the energy requirements of the system. LCA impacts for the AWG may be reduced through utilization of low environmental impact electrical energy options. While AWG units have substantial upfront capital costs, cost results are lower for the AWG unit compared to bottled water options purchased from commercial locations when amortized over the AWG's lifetime.

ACRONYMS AND ABBREVIATIONS

AWG	Atmospheric Water Generator
CAMX	Western Electricity Coordinating Council California, eGRID subregion
DQI	Data quality indicator
EF	Emission factor
eGRID	Emissions & Generation Resource Integrated Database
EPA	Environmental Protection Agency (U.S.)
ERG	Eastern Research Group, Inc.
FDA	Food and Drug Administration
FEMA	Federal Emergency Management Agency
FRCC	Florida Reliability Coordinating Council, eGRID subregion
GHG	Greenhouse gas
GWP	Global warming potential
HOD	Home/Office Delivery
ISO	International Standardization Organization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LDPE	Low-density polyethylene
MCF	Methane conversion factor
OPP	Oriented polypropylene
PC	Polycarbonate
PET	Polyethylene terephthalate
PM	Particulate matter
PP	Polypropylene
QAPP	Quality assurance project plan
RFCW	Reliability First Corporation West, eGRID subregion
RO	Reverse osmosis
SW	Solid waste
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental Impacts
US LCI	United States Life Cycle Inventory Database
UV	Ultraviolet

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1. Goal and Scope Definition

Across the U.S., there is a need to provide potable drinking water to communities in situations where treated municipal water is not accessible or is compromised. Traditionally, bottled water has been supplied to affected populations in the U.S., but there are some emerging technologies, such as atmospheric water generators (AWGs) that can produce water on-site using ambient humidity and energy supply from the electrical grid. While such systems are still in early stages of production and use, the findings of this study can help identify hotspots in the life cycle stages of AWGs in order to evaluate their environmental impact and cost as a source of drinking water supply in disaster/emergency situations. This study also compares the relative environmental and cost performance of AWGs, single-serve bottles, and multi-serve reusable jugs as emergency water supply options.

1.1 Introduction and Objective

This study investigates a novel technology called AWG that uses water harvesting to condense humidity from ambient air and generate potable water. AWGs can be used for supplying water as an emergency response option. The objective of this study is to evaluate the efficacy and performance of AWG technology in comparison with bottled water as an emergency response option to provide clean and safe drinking water for a long-term contamination situation. Using life cycle assessment (LCA), we compare the environmental LCA metrics associated with two different configurations of the AWGs and two types of commercially available bottled water options to provide context for understanding the outcomes associated with providing potable drinking water in long-term contamination emergency situations. All AWG systems are modeled as connected to the electrical grid. Weather related emergency situations such as hurricanes and tornados, that cause power outages, and require a rapid response were not examined in this study.

As one of the largest federal water research and development laboratories in the United States, the Environmental Protection Agency (EPA) generates innovative solutions that protect human health and the environment. The Office of Research and Development's (ORD) Safe and Sustainable Water Resources (SSWR) Program is the principal research lead seeking metrics and tools to compare the tradeoffs between economic, human health, and environmental aspects of current and future municipal water and wastewater services. A comprehensive systems-level analysis such as LCA can support the decision-making process for determining the mechanism for emergency potable water delivery.

LCA is a widely accepted method to assess the environmental aspects and potential impacts associated with individual products, processes, or services. It provides a "cradle-to-grave" analysis of environmental impacts and benefits that can better inform and assist in selecting the most environmentally preferable choice among the various options. The steps for conducting an LCA include (1) identifying the goal and scope, (2) compiling a life cycle inventory (LCI) of relevant energy and material inputs and environmental releases and emissions, (3) evaluating the potential environmental impacts associated with identified inputs and releases, and (4) interpreting the results to help individuals make more informed decisions.

The investigated LCA-related impacts include acidification potential, global warming potential (GWP), eutrophication potential, smog formation potential and particulate matter formation potential, and are based on the EPA's Tool for Reduction and Assessment of Chemicals and other environmental Impacts (TRACI) 2.1 life cycle impact assessment (LCIA) method (Bare et al., 2003). Fossil fuel depletion and water consumption are based on the ReCiPe[1] method; solid waste by weight is based on cumulative solid waste inventory; and cumulative energy demand is based on the cumulative energy inventory method of Ecoinvent (Frischknecht et al., 2007). These metrics are discussed in detail in Section 1.2.4. A cost analysis is also conducted and discussed in the results section.

1.2 Scope

This study design follows the guidelines for LCA provided by ISO 14040/14044 (ISO, 2006 a,b). The following subsections describe the scope of the study and the functional unit used for comparison (i.e., basis of results), system boundaries of analysis, LCIA methods, impact assessment categories, and potential data sources. The scope of this study is to compare an alternative potable water emergency response option of AWG with single-serve and multi-serve bottled water. This section lists the AWG and bottled water systems studied, their associated system boundaries, and potential data sources for the analysis. No other emergency water purification technologies such as reverse osmosis-based filtration, cartridge filtration systems, solar pasteurizations systems or natural filtration systems were assessed in this study. The geographic scope of this study is production and use in the United States with four regional electrical grid locations selected to assess the impacts associated with the operation of the AWG. The AWG water production varies with ambient temperature and humidity levels, which is discussed in detail in Section 3.1. The environmental impact of removing moisture from the air is outside the scope of this report.

1.2.1 Functional Unit

To provide a basis for comparison of different products, a common reference unit must be defined. The reference unit is based upon the function of the products, so that comparisons of different products are made on a uniform basis. This common basis, or functional unit, is used to normalize the inputs and outputs of the LCA, with all results expressed on a functional unit basis. Because the goal of AWG systems and bottled water is to deliver clean and safe drinking water, the functional unit of this study is *one liter of potable water at ambient temperature*. No cooling or heating of the potable water is considered in the functional unit calculation. There may be differences in the water quality characteristics of the AWG product versus bottled water. Such variations will not affect the functional unit. Note that bottled water and AWG product are not managed by EPA's National Primary Drinking Water Regulations. Bottled water is regulated by the Food and Drug Administration (FDA).

[1] "The name of this method "ReCiPe" is derived from two factors. First, the method provides a recipe to calculate life cycle impact categories. Second, the acronym represents the initials of institutes that were the main contributors: RIVM and Radboud University, CML, and PRè" (Goedkoop et al., 2009).

1.2.2 System Descriptions of Atmospheric Water Generators

The system boundaries of an AWG system are shown in Figure 1. The system boundaries start at production of the AWG unit, and continue through transportation to point of use, water generation, maintenance, and disposal of the AWG unit at end-of-life. Material, fuel, energy, and chemical inputs as well as air, water and waste outputs across all life cycle stages of the AWG are incorporated in the analysis. AWG infrastructure burdens are accounted for by amortizing infrastructure impacts by the useful life of the AWG unit and then standardizing results based on the functional unit of one liter of delivered potable water.

The main end use of AWG varies with scale. The large or industrial scale AWGs such as the Watergen Large Scale Water Generator and the EcoloBlue 1000 series, capable of generating up to 10,000L of water a day, can serve small towns to cities when set up as water stations especially in times of a natural disaster or emergency situations. They can also be used for irrigation of greenhouses, vertical farms, and hydroponics. These units are scalable and can be set up in multiples to meet high water needs. In addition, these industrial-scale units can be used in schools, hospitals, commercial or residential buildings, whole villages, factories, and off-grid settlements. These units can also be installed on the roof tops of buildings and retrofitted to deliver water directly to the kitchen via the internal piping system (Watergen). The medium-scale units such as the Gen-350 and EcoloBlue 100 series are mobile and can be easily transported for installation for home or business use. The EcoloBlue AWGs can be integrated with portable generators or renewable energy sources (wind, PV) for off-grid usage. The home/office scale AWG units such as Watergen Genny and EcoloBlue EB30 series are designed for indoor home or office use to replace bottled water or water fountains. We have also incorporated a number of scenarios around the electrical grid mix used, scale, water production, and the washing methods of container used to drink the water from an AWG.

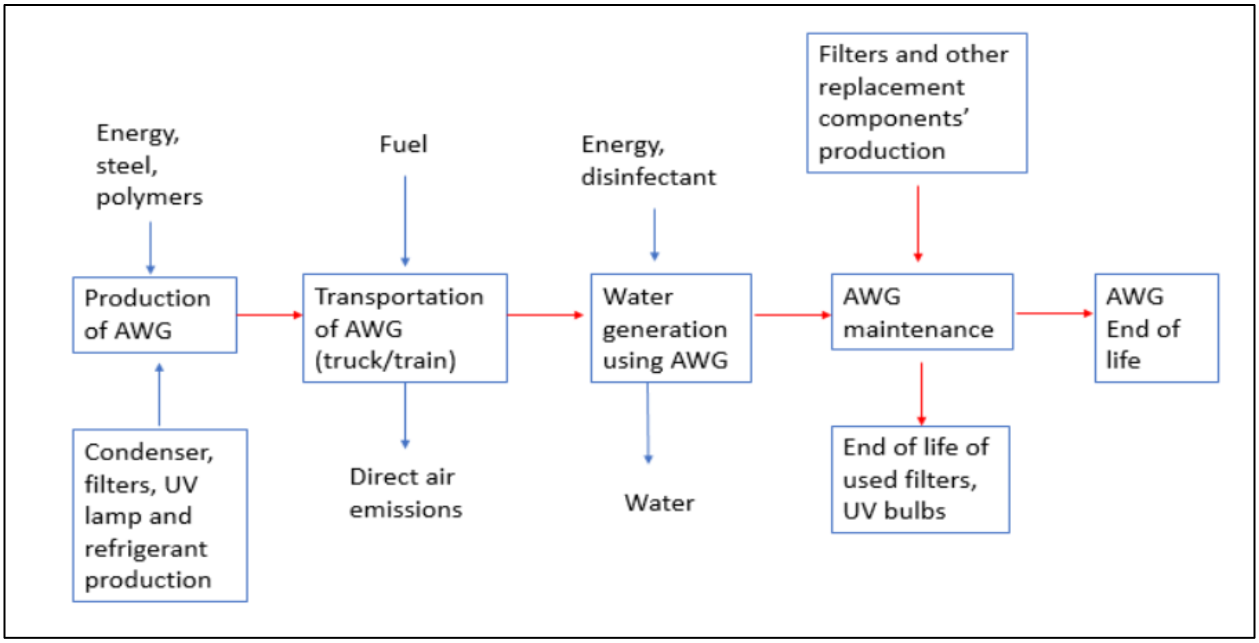


Figure 1. System boundary for atmospheric water generator.

1.2.2.1 AWG Vendors and Unit Scales

The study evaluates different AWG vendors to capture the range of potential environmental and cost impacts of this technology option. Eastern Research Group, Inc. (ERG), in coordination with EPA, identified the following possible vendors:

- **Watergen©:** Watergen manufactures AWG units of large (i.e., industrial), medium and home/office scale. The large-scale or industrial-scale units produce 3,000 L per day (with a maximum of 5,000 L per day) given optimum levels of temperature (27 degrees Celsius) and humidity (60 %) and can be installed on the rooftops of commercial buildings, in multiples, to meet high water demands. The medium scale unit, Gen-350, is a portable AWG which can be mounted on a small truck or an SUV and allows for generation of up to 400 L water per day. The home or office scale unit, Genny, is able to generate 25 L of water daily.
- **EcoloBlue™[2]:** EcoloBlue manufactures AWG units of large, medium and home/office scale. The large-scale units range from 10,000 L produced per day to 1,000 L per day given optimum levels of temperature (30 degrees Celsius) and humidity (80 %). These units are scalable to meet high drinking water demands. The medium scale units or the light industrial series come in 100 L, 300 L and 600L per day options. The home- or office-scale units can generate up to 30 L of water daily in

[2] It is important to mention that the company Ecoloblue is not operational any longer, but it was operating at the time this study was conducted. The additional data points from Ecoloblue are useful for determining a range of AWG LCA results.

optimal conditions. All EcoloBlue units are capable of integration with alternative power sources such as portable generators, wind, and photovoltaic solar panels.

Figure 2 and Figure 3 show the unit processes of two different AWG units developed by Watergen and EcoloBlue, respectively. The specific treatment of the water prior to delivery depends on the AWG design and unit scale. All systems are modeled as connected to an electrical grid for the purposes of this study. Assessment of alternative energy sources such as a diesel generator or renewable solar options are outside of the current project scope, but may be considered in later phases.

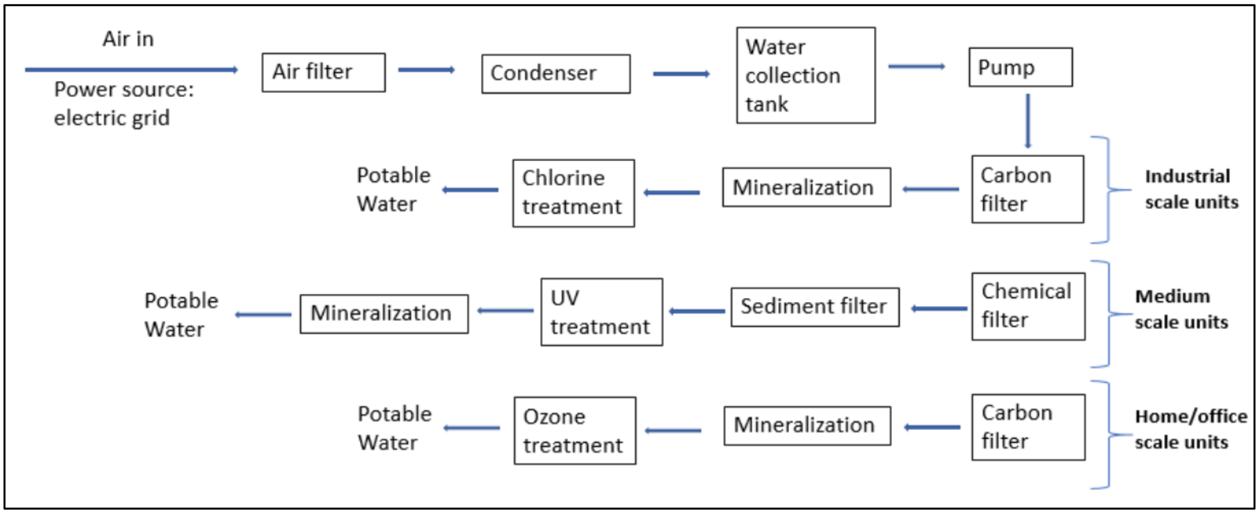


Figure 2. Schematic overview of AWG unit operation – Watergen.

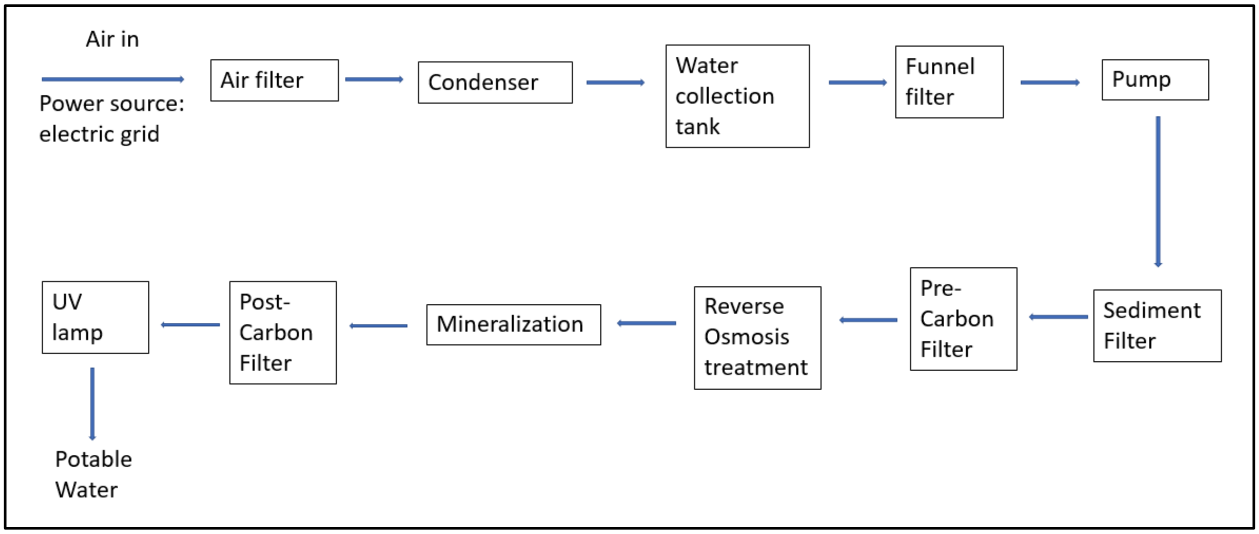


Figure 3. Schematic overview of AWG unit operation – EcoloBlue (all scales).

The vendor specific parameters used in the LCA model are listed in Table 1.These data were provided directly by the vendors (Watergen and EcoloBlue) in the form of vendor specific reports, completed data forms, via e-mail communication, or provided on the vendors' official websites. The data parameters for daily volume of water generated were varied in a sensitivity analysis to study the impacts associated with low or high daily volume of water produced by the AWGs (see Section 4.4 for details).

Table 1. Vendor Specific LCA Parameters

Vendor	Scale	Weight (kg)	Volume Generated (L per day)	Electricity per Volume Produced (Wh/L)	Unit Cost (2018 USD)§	Maintenance Cost per Year (2018 USD)*
Watergen	Large	2,870	3,000‡	350	$115,000	$7,866
Watergen	Medium	800	400	330	$55,000	$2,500
Watergen	Home/Office	50	25	300	$1,250	-
EcoloBlue	Large	3,800	3,000	420	$159,700	$3,767
EcoloBlue	Medium	1,000	600	410	$30,750	$870
EcoloBlue	Home/Office	50	30	300	$799†	-

*Maintenance cost of AWGs includes filters replacement and disinfection of internal tanks.

†The default parameters for the EcoloBlue home/office unit are associated with Ecoloblue30E, there are two other units produced in this category called Ecoloblue30X and Ecoloblue30X Alkaline and their unit costs are $1299 and $1499 respectively.

‡ This volume is reported in multiple sources and selected as per the data provided directly to ERG by Watergen and the Watergen large scale AWG brochure available at the time of the project. Maximum water production for the large scale unit is modeled as up to 5,000 liters/day in a sensitivity analysis as specified in Table 6.

§Unit cost includes the cost of external tanks that are purchased with the large-scale units.

1.2.3 System Descriptions of Bottled Water Production

The comparative bottled water analysis includes both a single-serve and a multi-serve option. The main parameters for these two bottled water options in the baseline analysis are displayed in Table 2. The primary packaging option for single-serve bottled water delivery is polyethylene terephthalate (PET) plastic bottles and for the multi-serve large polycarbonate (PC) jugs are typically used for home/office delivery (HOD). Two sizes of bottles are considered in this study; for the single-serve option a 500 ml (16.9 oz) PET bottle is studied and for the multi-serve an 18.9 L (5 gallon) PC water jug is studied. The baseline analysis for the single serve bottle assumes a 16.9 oz bottle (9.3g) modeled based on a lightweight domestic spring water system. For determining sensitivity of the LCA results to bottle weight, an additional 16.9 oz (10.9g) lightweight bottle is modeled based on an alternative water brand. While the packaging weights and supply chain for alternative bottled spring water were based on specific brands, no primary data were collected from these brands for this study. The baseline analysis for single-serve bottle also assumes 0% recycled content of the primary bottle material, however, 10% recycled content is also modeled for sensitivity analysis (McKay, 2008). The single-serve bottles include a polypropylene (PP) closure and are configured in 24-count multipacks with shrink wrap distribution packaging. The baseline weight and material of the empty HOD bottle and closure material were acquired from publicly available e-commerce listings. The HOD bottles are used by consumers in combination with a reusable glass. The HOD bottles have approximately 40 lifetime uses (ORDEQ, 2009). The water within the bottles is modeled as either spring water or purified municipal water. In many cases, bottled water plants treat municipal water with additional purification steps such as ozone treatment and UV treatment (ORDEQ, 2009). The percentages of postconsumer waste that is recycled and disposed after use are based on U.S. data from the U.S. EPA "Advancing Sustainable Materials Management Report" (U.S. EPA, 2016). The recycling rate of the single-use bottle is modeled as 31.3%. The HOD bottle is modeled with 100% recycling, since the bottles are managed by delivery services. For all packaging waste that enters the municipal waste stream, 82.2% are managed in a landfill and 17.8% are sent to waste to energy incineration based on average U.S. conditions (U.S. EPA, 2016).

Table 2. Bottled Water Systems Studied

	Single-Serve Water Bottle	Multi-Serve Water Bottle
Volume	500 ml (16.9 oz)	18.9 L (5 gallons)
Primary bottle material	polyethylene terephthalate	polycarbonate
Empty bottle weight (g)	9.3	794 (1.75 lbs)
Closure material	Polypropylene	LDPE
Closure weight (g)	1.1	14.5
Type of water	Purified municipal water or spring water with ultrafiltration, ozone treatment, and UV.	
Label material	PP	n/a
Label weight (g)	0.6	n/a
Multipack	24-count	n/a
Multipack packaging	Shrink wrap (LDPE)	n/a
Shrink wrap weight (g)	31.5	n/a
Type of reusable drinking container	Not applicable	475 ml (16.1 oz) glass
Recycling rate	31.3%	100%
Lifetime uses	1	40
Transport distance*	100 mi	75 mi

*Transport of bottled water from filling location to the consumer. Transport is modeled in a diesel combination truck for single-serve bottles. The HOD bottles are transported in smaller vans by a delivery service.

The cost of bottled water to the consumer is based on the price of a 24-pack for single-serve PET bottles as sold at a large-scale grocery chain and the price of a 5-gallon spring water jug sold by various vendors as a home/office delivery service. The costs are listed in Table 3. In emergency situations where the public water supply is rendered non-potable or inaccessible, various organizations within the U.S. government have historically been responsible for delivering water to the affected citizens. For example, the National Guard delivered water and water filters door-to-door and in schools during the Flint water crisis and the cost of water supply was covered by the state of Michigan (Maher, 2016). Similarly, during the hurricane Maria, Federal Emergency Management Agency (FEMA), Federal Bureau of Investigation (FBI) and United States Army Reserves provided bottled drinking water to survivors in Puerto Rico (Baja, 2017). Based on recent water disasters locally and internationally it appears that states handle contaminated local water, and federal entities typically handle weather disasters (U.S. EPA, 2011).

Table 3. Sample Cost of Water Bottles

Brand Name	Type of Product	Price per Pack (16.9oz)/5-gallon bottle ($)	Delivery Cost per Month ($)
Poland Spring*	16.9 oz, 24 pack	$4.49	-
Dasani*	16.9 oz, 24 pack	$3.99	-
Belmont Springs/ Crystal Rock[§]	5 gallon, purified water	$6.99	$5
Belmont Springs/ Crystal Rock[§]	5 gallon, spring water	$7.99	$5
Poland Spring[§]	5 gallon, spring water	$7.49	$6.95
Nestle Pure Life[§]	5 gallon, purified water	$6.49	$6.95
Wegmans Spring*	4 gallon, spring water	$3.99	-

*These products were sampled at Wegmans in Burlington, MA on Tuesday, September 11, 2018.

[§]The data for these products were acquired by calling vendors for pricing on Wednesday, September 12, 2018.

The system boundaries for the single-serve bottled water analysis are shown in Figure 4. The system boundaries start at spring water extraction or municipal drinking water treatment. The bottled water plant conducts additional purification steps prior to filling such as ultrafiltration, ozone treatment, and UV treatment. The system boundaries include raw material production of virgin primary packaging and associated components such as PET for the bottle, PP for the cap, and oriented polypropylene (OPP) for the label. The system boundaries also include raw material production and conversion for distribution packaging materials such as low-density polyethylene (LDPE) for the shrink wrap. The model assumes that PET is injection molded to a preform at a separate facility and then stretch blow molded to a bottle at the filling location. After filling and application of the shrink wrap multipack packaging, the bottles are transported to the point of use. The model does not include any refrigeration of the bottled water. Bottles and multipack packaging are either recycled or disposed at end-of-life. Note that all life cycle stages requiring electricity in the bottled water systems are modeled with the U.S. average electrical grid fuel mix.

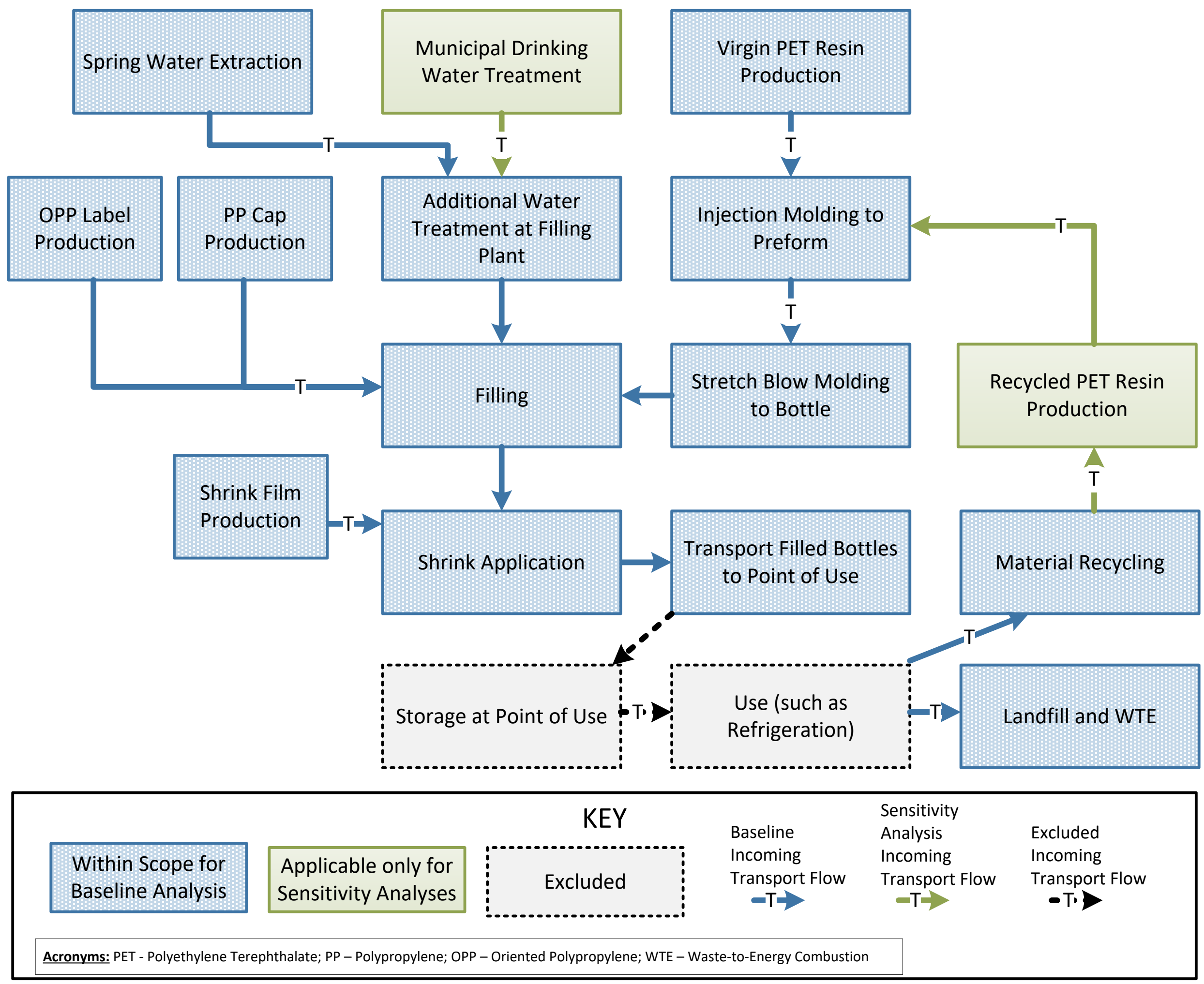


Figure 4. System boundary for single-serve bottled water analysis.

The system boundaries for the multi-serve HOD jug/bottle are shown in Figure 5. Water treatment is modeled using the same approach as the single-serve analysis. Filled HOD jugs are transported to point of use via a delivery service van. The analysis assumes consumers use a reusable glass to fill drinking water from the jugs. After use, the glass is assumed to be cleaned by handwashing in the baseline analysis however, use of soap is outside the scope of this study. Section 4.4.1.2 includes a sensitivity analysis addressing the option of no washing in emergency conditions pertaining to water shortages. Use of dishwashers is also considered to be an un-viable option in emergency situations especially when replacing large-scale water supply. After the jug is empty, the same delivery service collects the jug from the point of use. It is assumed the jug cap is disposed and the jug itself is sent back to the filling facility. Prior to filling the jug, the jug goes through an industrial washing process. Industrial washing between uses includes the production of relevant cleaning chemicals. The jugs are used approximately 40 times until they are recycled by the delivery service. It is assumed the reusable glass for drinking is reused for 3 years, once a day, for 1,095 total lifetime uses. Material production requirements for the jug are amortized over the useful life of the components. Given the notable number of lifetime uses for the reusable glass, production and disposal of the glass are assumed negligible, and excluded from the model. The refrigeration of water after being poured out of the reusable jug is also excluded from the analysis.

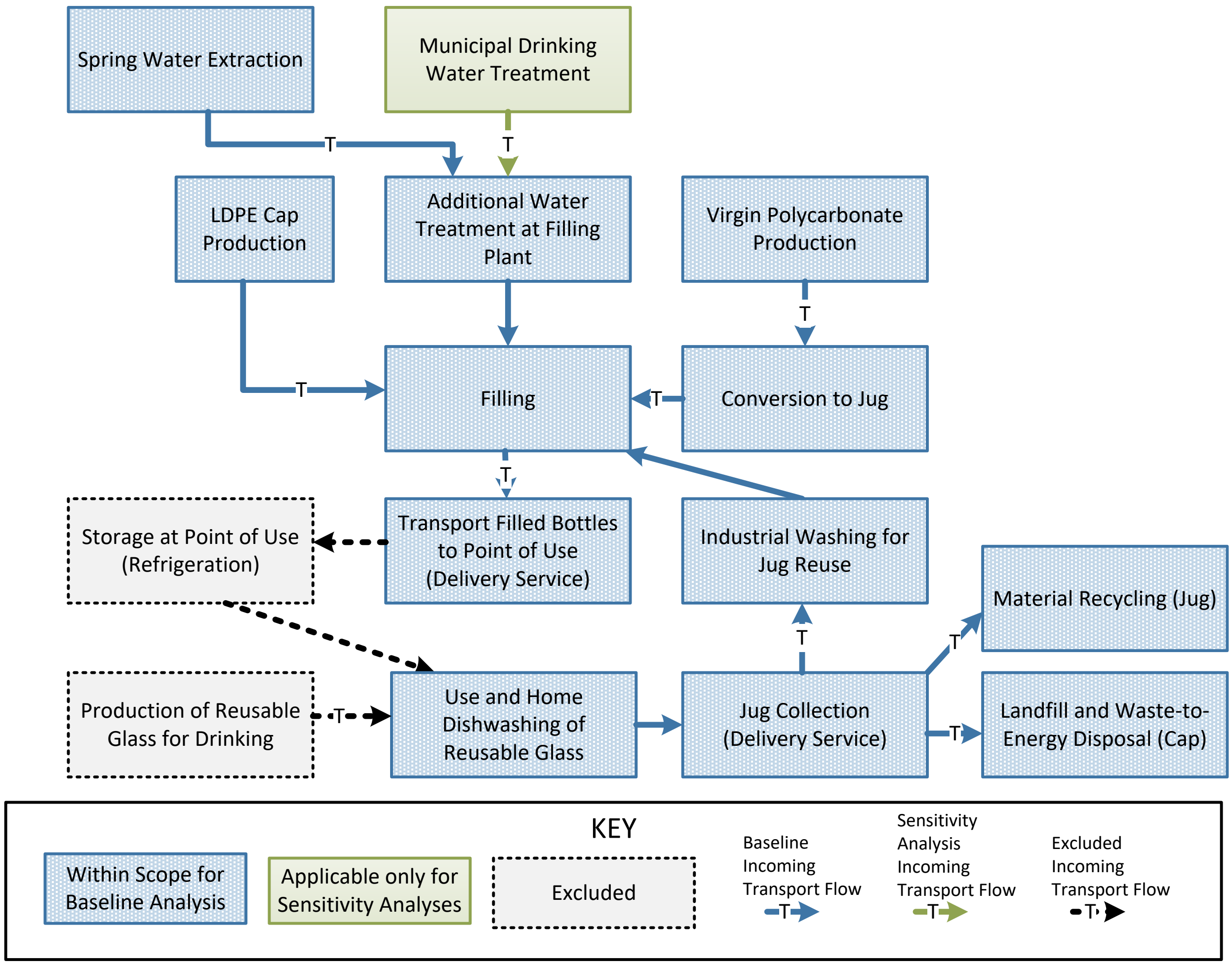


Figure 5. System boundary for multi-serve home delivery jug analysis.

1.2.4 Metrics and Life Cycle Impact Assessment

LCIA helps with interpretation of the emissions inventory. LCIA is defined in ISO 14044 Section 3.4 as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product." In the LCIA phase, the inventory of emissions is first classified into categories in which the emissions may contribute to impacts on human health or the environment. Within each impact category, the emissions are then normalized to a common reporting basis, using characterization factors that express the impact of each substance relative to a reference substance.

In addition to the LCIA, a cost analysis was also carried out to compare the standardized cost of each system per liter of water. The details of this analysis are provided in Section 4.5. This analysis used net present value of the cost of the AWGs over their lifetimes to calculate the per liter cost based on the average number of liters produced by the units over their lifetimes. The per liter cost of bottled water is based on unit price and quantity sold in the market.

The results of this study address global, regional, and local impact categories. The impact categories and methods applied in this study along with their units and a brief description of each category are shown in Table 4. The TRACI version 2.1 LCIA method, developed by the U.S. EPA specifically to model environmental and human health impacts in the U.S., is the primary LCIA method applied in this study (Bare, 2003). Additionally, the ReCiPe LCIA method is used to characterize fossil fuel depletion and water use (Goedkoop et al., 2009). Energy is tracked based on point of extraction using the cumulative energy demand method developed by Ecoinvent (Frischknecht et al., 2007).

Table 4. Scope of Impact Assessment

Category	Unit	Method	Description
Acidification Potential	kg SO_2 eq	TRACI v2.1	Quantifies the acidifying effect of substances on their environment. Important emissions: SO_2, NO_x, NH_3, HCl, HF, H_2S.
Cumulative Energy Demand	MJ-eq	Ecoinvent	Accounts for the total usage of non-renewable fuels (natural gas, petroleum, coal, and nuclear) and renewable fuels (such as biomass and hydropower). Energy is tracked based on the heating value of the fuel utilized from point of extraction, with all energy values summed together and reported on a MJ basis.
Eutrophication Potential	kg N eq.	TRACI v2.1	Assesses impacts from excessive load of macro-nutrients to the environment. Important emissions: NH_3, NO_x, COD and BOD, N and P compounds.
Fossil Fuel Depletion	kg oil-eq.	ReCiPe	Captures the consumption of fossil fuels, primarily coal, natural gas, and crude oil. All fuels are normalized to kg oil equivalent (eq) based on the heating value of the fossil fuel and according to the ReCiPe impact assessment method.
Global Warming Potential	kg CO2-eq.	TRACI v2.1	Represents the heat trapping capacity of GHGs over a 100-year time horizon. All GHGs are characterized as kg CO2 equivalents using the TRACI 2.1 method. TRACI GHG characterization factors align with the IPCC 4th Assessment Report for a 100-year time horizon.
Particulate Matter Formation Potential	kg PM2.5 eq	TRACI v2.1	Determines the effect of particulate matter (e.g., PM 2.5 and PM10) and pollutants which lead to respiratory impacts related to particulates (e.g., sulfur oxides and nitrogen oxides).
Smog Formation Potential	kg O_3 eq.	TRACI v2.1	Determines the formation of reactive substances (e.g. tropospheric ozone) that cause harm to human health and vegetation. Important emissions: NO_x, BTX,

Table 4. Scope of Impact Assessment

Category	Unit	Method	Description
			NMVOC, CH_4, C_2H_6, C_4H_{10}, C_3H_8, C_6H_{14}, acetylene, Et-OH, formaldehyde.
Solid Waste by Weight	kg	Cumulative solid waste inventory	Measures quantity of fuel, process and postconsumer waste to a specific fate (e.g., landfill, waste-to-energy incineration) for final disposal on a mass basis.
Water Consumption	m^3 H_2O	ReCiPe	Quantifies the volume of fresh water inputs to the life cycle of products within the supply-chain. An inventory category, that does not characterize the relative water stress related to water withdrawals. Adapted from the water depletion category in the ReCiPe impact assessment method.

2. METHODS

This section covers the data collection process, data sources, assumptions, methodology and parameters used to construct the LCI model for this study. Data used to construct the AWG and bottled water inventories are described in Section 2.1 and 2.2, respectively. Modeling procedures as well as data quality assessment and limitations are described at the end of the chapter.

For background processes such as material production, energy, and transport, ERG has used credible published LCI databases such as: the National Renewable Energy Laboratory's (NREL) U.S. LCI and the EPA ORD LCA database. For unit processes for which public data are not available, we have cited the private data sources and disclosed as much information as possible without compromising the confidentiality of the data source. An example of a private LCI database is the Ecoinvent database (Weidema et al., 2013). Where data from the Ecoinvent database are used, we have adapted the data, so they are consistent with other data modules used in the study and representative of the energy production and transportation and, if applicable, industry practices in the U.S.

2.1 AWG Life Cycle Inventory Data Sources

ERG collected existing data from vendors to construct the AWG inventory. Data sources and modeling assumptions are described by life cycle stage in the subsequent sections.

2.1.1 Capital Equipment

It is assumed that most of the composition of the AWGs is stainless steel. The weight of the AWG units for specific scales is provided by the vendors. The weight includes weight of steel, filters, UV lamps and the refrigerants. Based on the data provided by the specific vendors, the filters are replaced every six months and UV lamps every year; therefore, the number of filter and UV lamp replacements are calculated per lifetime of the unit. The lifetime of the EcoloBlue unit is 20 years and the Watergen lifetime is 10 years. Specific capital equipment weight factors used are provided in 6.Appendix A. No information on energy requirements for assembling the AWG units was available.

2.1.2 Transportation to Point of Use

The transportation of the AWG units from the point of manufacture to the point of use is based on vendor provided information. Currently, the Watergen AWG units are manufactured in Columbia, South Carolina and those of EcoloBlue, in California. Due to the lack of primary transportation data, an average distance of 160 km (100 miles) is assumed for transportation of AWG units to the point of use. Primary mode of transportation assumed is a combination truck using the average fuel mix for the U.S. (diesel), but the openLCA model can switch to rail and/or ocean freight if applicable.

2.1.3 Operation

The operational life stage of AWG includes running the unit on grid electricity and producing water that is treated by the filtration system within each unit. The data on kWh usage by each unit to produce a liter of water, for a given scale, is provided by the vendors and is used to parameterize the model (6.Appendix A). The baseline model AWG operation uses the average U.S. electrical grid fuel mix. The current electrical grid mix consists largely of fossil fuels with highest dependency on coal (38.7 percent), followed by natural gas (27.5 percent). Nuclear energy contributes 19.5 percent to the grid and all other renewable energy sources make up 13 percent, which include hydropower, solar, wind, geothermal and biomass (U.S. EPA, 2014). Watergen has provided operational data for Gen-350 for Florida so the sub-region Florida Reliability Coordinating Council (FRCC), is incorporated in a sensitivity analysis around energy mixes. FRCC derives two-thirds of its electricity from natural gas, followed by coal, nuclear power, oil, and renewables, respectively (U.S. EPA, 2014). The renewable energy is sourced primarily from biomass, hydropower, and solar energy. Watergen has provided EPA with a medium-scale Gen-350 unit to collect operational data in Cincinnati, OH so the sub-region Reliability First Corporation West (RFCW) where Cincinnati is located is also included in the sensitivity analysis. ERG has also incorporated a scenario modeling a low emissions electricity option, which is also the location where the Ecoloblue units are manufactured. This scenario assumes that the AWG derives energy from Western Electricity Coordinating Council California (CAMX) which sources 62.5 percent of energy from natural gas, 8.4 percent from hydropower, 4.3 percent from solar, 9 percent from nuclear and only 0.4 percent from coal. The details of the resource mix for the average U.S. and the three sub-regions is shown in Table 5. A map of the eGRID subregions is also provided in Figure 6.

Table 5. EPA eGRID U.S. and Three Sub-Regions Electricity Generation Resource Mix 2014

eGRID subregion acronym	eGRID subregion name	Generation Resource Mix (percent)*										
		Coal	*Oil*	*Gas*	*Other Fossil*	*Nuclear*	*Hydro*	*Biomass*	*Wind*	*Solar*	*Geo-thermal*	*Other unknown*
U.S. Average		**38.7**	**0.7**	**27.5**	**0.4**	**19.5**	**6.2**	**1.6**	**4.4**	**0.4**	**0.4**	**0.1**
FRCC	**FRCC All**	21.7	0.8	61.4	0.6	12.7	0.1	1.9	0.0	0.1	0.0	0.7
RFCW	**RFC West**	60	0.5	9.3	0.7	25.7	0.6	0.6	2.4	0	0	0.1
CAMX	**WECC California**	0.4	0	62.5	0.8	9	8.4	3.4	6.5	4.3	4.4	0.3

*Percentages may not sum to 100 due to rounding.

Source: U.S. Environmental Protection Agency (EPA) (2014) Emissions & Generation Resource Integrated Database (eGRID) 2014 Summary Tables. https://www.epa.gov/energy/egrid-2014-summary-tables.

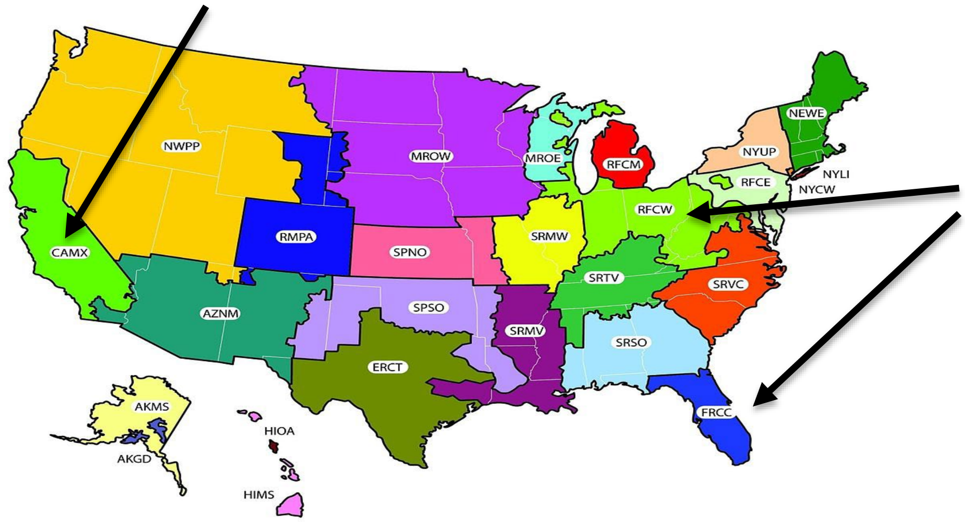


Figure 6. Map of eGRID subregions. Arrows point to subregions assessed for AWG operation.

2.1.4 Use and Reusable Container Washing

The primary water delivery method from the AWGs is filling bottles directly from the unit. We assume that a 16 oz reusable glass is used for delivery of the AWG water for drinking purposes and handwashed using water from the AWG when necessary. Given the significant number of potential lifetime uses of the glass, the production and disposal of the glass itself is outside of the system boundaries. Use of soap is also not included in handwashing of the glass in this study. The washing of the reusable glass is also incorporated in the scope for the multi-serve jugs. A sensitivity analysis modeling no washing of the glass is presented in Section 4.4.1.2.

2.1.5 Disposal

For the disposal of AWG units, we included the transportation of the AWG unit to the disposal site only. The assumed transportation distance is 160 km (100 miles) as vendor data on transportation distances were not available. The mode of transportation is diesel powered combination truck. Dismantling and recycling of subcomponents is outside the scope of this study. We modeled all components as recycled.

2.2 Bottled Water Life Cycle Inventory Data Sources

ERG developed the bottle water analysis using the bottled water life cycle and production of bottled water packaging materials sources as follows:

- **Municipal Drinking Water Treatment:** Cashman, S., Gaglione, A., Mosley, J., Weiss, L., Ashbolt, N., Hawkins, T., Cashdollar, J., Xue, X., Ma, C., and Arden, S. (2014). Environmental and cost life cycle assessment of disinfection options for municipal drinking water treatment. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/376

- **Spring Water Treatment, Reusable Jug and Plastic Bottle Assumptions:** Oregon Department of Environmental Quality. (2009). Life Cycle Assessment of Drinking Water Systems: Bottle Water, Tap Water, and Home/Office Delivery Water. Franklin Associates, A Division of ERG, 09-LQ-104
- **PET, LDPE, PP, HDPE Virgin Resin Production**: American Chemistry Council (ACC). (2011a). Cradle-to-Gate LCI of Nine Plastic Resins and Two Polyurethane Precursors. Franklin Associates, A Division of ERG. http://plastics.americanchemistry.com/LifeCycle-Inventory-of-9-Plastics-Resins-and-4-Polyurethane-Precursors-Rpt-Only
- **PET Recycled Resin Production:** Franklin Associates. (2011). Life Cycle Inventory of 100% Postconsumer HDPE and PET Recycled Resin from Postconsumer Containers and Packaging.
- **Plastic Conversion Processes**: ACC. (2011b). Life Cycle Inventory of Plastic Fabrication Processes: Injection Molding and Thermoforming. Franklin Associates, A Division of ERG. https://plastics.americanchemistry.com/Education-Resources/Publications/LCI-of-Plastic-Fabrication-Processes-Injection-Molding-and-Thermoforming.pdf.

2.3 LCA Modeling Procedure

Development of an LCA requires significant input data, an LCIA modeling platform, and impact assessment methods. Each unit process in the LCI was constructed independently of all other unit processes. This allows objective review of individual data sets before their contribution to the overall life cycle results has been determined. In most cases, individual unit processes were parameterized to dynamically represent multiple scales and configurations.

The model was constructed in openLCA Version 1.7.0, an open-source LCA software package provided by GreenDelta (GreenDelta, 2017). This open-source format allows seamless sharing of the LCA model between project team members. Once all necessary data including the primary data collected from the vendors and data assumed for this study were input into the openLCA software and reviewed, system models were created for each technology type, scale and configuration. The models were reviewed to ensure that each elementary flow (e.g., environmental emissions, consumption of natural resources, and energy demand) was characterized under each impact category for which a characterization factor was available. The system models were also reviewed prior to calculating results to make certain all connections to upstream processes and weight factors were valid. LCIA results were then calculated by generating a contribution analysis for the selected treatment configuration product system based on the defined functional unit of treatment of 1 liter of drinking water. Results were exported to a dynamic Excel workbook (6.Appendix B).

2.4 Cost Analysis

This study also includes a standardized per liter cost calculation for all the systems studied. The standardized price per liter of water for AWG includes a net present cost calculation of the unit price of the AWG unit and the maintenance and energy costs over the lifetime of the AWG (ten years for Watergen units and 20 years for EcoloBlue units). This discounted cost is then used to calculate the per liter cost based on the average total volume of water produced by the AWG over its lifetime. The unit and maintenance costs are provided by the vendors and the cost of electricity is calculated for the AWGs based on the U.S. average price of electricity (10.82 cents per kWh; EIA, 2018). These costs are discussed in detail in Section 4.5. The standardized cost for bottled water is based on the unit price of a 24 pack (12 liters) for the single-serve bottle selected for the Poland Spring brand and the Poland Spring 5 gallon jug (18.9 liters). The monthly flat rate delivery charge is also included in the per liter cost of the reusable jug, but it is based on the assumption that 4 jugs are delivered in a month (this amount varies by household). In addition, 54.5 cents per mile of transporting the single-serve bottle was added to the per liter cost based on the US government standard mileage reimbursement rate (IRS, 2018).

2.5 Data Quality and Limitations

In accordance with the project's Quality Assurance Project Plan (QAPP) entitled *Quality Assurance Project Plan for Life Cycle Considerations and Systems Analyses of Municipal Water Sustainability Assessments* approved by EPA on May 9, 2018, ERG collected existing data[3] to develop the LCA and cost estimates for the study and associated sensitivity analyses. ERG evaluated the collected information for completeness, accuracy, and reasonableness. Finally, ERG performed developmental and final product internal technical reviews of the LCA and costing methodology and calculations for this study.

ERG input all LCI data developed into the openLCA v1.7.0 software (GreenDelta, 2017). A team member knowledgeable about the project, but who did not develop the model, reviewed the openLCA model to ensure the accuracy of the data transcribed into the software.

LCI information that falls outside of the system boundary include installation or moving the AWG from the location of delivery to the location of use such as the use of forklift etc. Assembly of the AWG unit following raw material production is excluded due to lack of available data. Also excluded are potential delivery systems such as the use of plastic disposable cups as opposed to reusable glass container for drinking water or retrofitting the delivery of water from AWG into the existing pipe infrastructure of a building. Additionally, the production and disposal of the glass container is excluded from the analysis. More general LCI limitations that readers should understand when interpreting the data and findings are as follows:

- **Transferability of Results.** While this study is intended to inform decision-making around best options for potable water supply in times of emergencies, the data presented here relates to specific AWG vendors and bottled water available in the market. Further work is recommended to understand the variability of key parameters across different environmental conditions and parameter configurations. The results are only intended to address the specific indicators covered. Other potential benefits of the AWG system, such as accessibility in emergency conditions, are not addressed and should be investigated separately.

[3] *Existing data* means information and measurements that were originally produced for one purpose that are recompiled or reassessed for a different purpose. Existing data are also called secondary data. Sources of existing data may include published reports, journal articles, LCI and government databases, and industry publications.

- **Representativeness of Background Data.** Background processes are representative of either U.S. average data (in the case of data from U.S. EPA or U.S. LCI) or European average (in the case of Ecoinvent) data. In some cases, European Ecoinvent processes were used to represent U.S. inputs to the model due to lack of available representative U.S. processes for these inputs. The background data, however, met the criteria listed in the project QAPP for completeness, representativeness, accuracy, and reliability.
- **Data Accuracy and Uncertainty.** In a complex study with thousands of numeric entries, the accuracy of the data and how it affects conclusions is truly a difficult subject, and one that does not lend itself to standard error analysis techniques. The reader should keep in mind the uncertainty associated with LCI models when interpreting the results. Comparative conclusions should not be drawn based on small differences in impact results. A number of sensitivity analyses were conducted to address uncertainty in the inventory inputs.

3. SCENARIO AND SENSITIVITY ANALYSES

LCAs inherently involve making assumptions. To test the influence of the assumptions made in an LCA model, it is important to conduct sensitivity analyses. To carry out a sensitivity analysis, the assumption of interest is changed and the entire LCA is recalculated. A sensitivity analysis helps interpret the magnitude of the effect of an assumption on the LCA results. The subsequent sections describe the sensitivity analyses conducted for the AWG and bottled water systems, respectively. Sensitivity analyses results are discussed in Section 4.4.

3.1 AWG Scenarios Evaluated

ERG has included multiple options for the location of AWG use as climate conditions such as temperature and relative humidity may affect the AWG performance. Most AWGs operate well in temperatures ranging from 0 to 60 degrees Celsius and relative humidity between 25 and 100 percent. We have modeled the minimum and maximum volume produced for a range of temperature and relative humidity combinations for the AWG units and scales provided by the vendors. We also ran scenarios representing the four eGRID locations selected for the AWG units (see Section 2.1.3 for details).

The relative humidity and temperature may vary slightly for LCAs developed for AWG scales and/or vendors based on available data. The AWG performance by scale and under varying relative humidity and temperature ranges are provided in Table 6.

Table 6. AWG Performance by Scale and Vendor

Vendor	Watergen			EcoloBlue		
Scale	**Large**	**Medium**	**Small**	**Large**	**Medium**	**Small**
Maximum Water Produced (L/day)	5,000	578	25	4,781	962	30
Minimum Water Produced (L/day)	3,000	38	15	193	50	20
Modeled value Water Produced (L/day)	3,000	400	25	3,000	600	30
Relative Humidity Range (%)	60	20-70	60	30-80	30-80	0-60
Temperature Range (°C)	26.7	15-40	26.7	0-55	0-55	25-100

For the washing of the glass container, the scenarios include handwashing and no washing of the container. Handwashing (baseline) was modeled assuming 8 oz of water are required for each washing cycle of the 16 oz glass. The handwashing of the reusable glass is also incorporated in the scope for the multi-serve jugs.

Table 7. Summary of AWG Scenarios

	WaterGen	EcoloBlue
Scale		
Large	✓	✓
Medium	✓	✓
Home/office	✓	✓
Electrical Grid Mix		
U.S. Average	✓	✓
FRCC	✓	✓
RFCW	✓	✓
CAMX	✓	✓
Water Production (function of relative humidity and temperature)		
Minimum*	✓	✓
Average*	✓	✓
Maximum*	✓	✓
Reusable Container Washing Method		
Handwash§	✓	✓
No washing	✓	✓

*The values of minimum, maximum and average values included in the model are shown in Table 6.

§Handwashing is modeled as using half the volume of the reusable glass for input water

3.2 Bottled Water Scenarios Evaluated

We have studied several scenarios around key assumptions in the bottled water analysis. All scenario results are compared to the AWG findings. The bottled water scenarios are shown in Table 8. The scenarios evaluated include washing methods of the reusable container (handwash versus no wash) for the multi-serve option, transport distances for delivering multi-serve water bottles, weights of the single-serve lightweight bottle, recycled content of the single-serve bottle (virgin versus ten percent), the recycling allocation methods (cut-off versus system expansion) and the source of water (spring water or treated municipal water) for filling the bottles.

The baseline scenario models lightweight single-serve bottles (9.3 grams and 10.9 grams) with virgin PET or zero recycled content. All recycled content or material recycling are modeled using the cut-off recycling allocation method (described below). The baseline analysis includes a 24-count multipack of single-serve bottles configured with shrink wrap and assumes the transport distance of the filled bottle to the consumer as an estimated 100 miles for the single-serve bottle and 75 miles for the multi-serve bottle based on the assumptions made in a life cycle assessment study by the State of Oregon Department of Environmental Quality, on drinking water systems (ORDEQ, 2009). The baseline analysis assumes that the water is derived from a spring and includes additional water treatment steps at the filling location such as ultrafiltration, ozone treatment, and UV treatment. The baseline analysis assumes 40 reuses of the HOD jug and that the reusable glass used in combination with the HOD jug is washed in by hand after use (ORDEQ, 2009).

Table 8. Bottled Water Scenarios

	Single-Serve Water Bottle	Multi-Serve Water Bottle
Reusable Container Washing Method		
Handwash*		✓
No Washing		✓
Transport Distance[§]		
Maximum (125 mi)		✓
Average (75 mi)*		✓
Minimum (25 mi)		✓
Bottle Weight (lightweight)		
Minimum (9.3 g)*	✓	
Maximum (10.9g)	✓	
Bottle Recycled Content		
0%*	✓	
10%	✓	
Recycling Allocation Method		
Cut-off*	✓	✓
System Expansion	✓	✓
Bottled Water Source		
Spring Water*	✓	✓
Treated Municipal Water	✓	✓

*Baseline scenario, [§]ORDEQ, 2009

The details of the bottled water baseline and sensitivity analyses are listed below:

- **Bottle weight:** single-serve bottle weights vary by brand, with some brands lightweighting PET bottled water packaging. Sampled primary packaging weights for 500 ml bottled water range from 9.3 grams to 23.4 grams. North American brands, most likely used for emergency response conditions, are typically lightweighted in the 500 ml single-serve size. Sensitivity analyses are not conducted for heavier PET bottles. The heavier PET bottles sampled typically represented premium bottled water options such as international spring and artesian water. Bottle weight is not varied in the multi-serve option.
- **Bottle recycled content and recycling allocation method:** A recycled content up to 10% is often seen in North American single-serve PET water bottles (McKay, 2008). We have included a sensitivity analysis with up to 10% recycled content in the single-serve bottles. When including recycled content, multiple approaches are available to partition (or allocate) impacts between the useful lives of a material. The cut-off

approach is used in the baseline analysis. Under this approach, distinct boundaries are drawn between the initial use of the material and subsequent uses of the material after recovery and recycling (U.S. EPA, 1993). All virgin material production burdens are assigned to the first use of the material, and the burdens assigned to the recycled system begin with recovery of the postconsumer material. For containers that are recycled at end of life, all of the burdens for material recovery, transport, separation and sorting, and reprocessing are assigned to the next system using the recycled material. Burdens associated with the final disposal of the product are assigned to the last useful life of the product. We have incorporated an alternative system expansion recycling allocation approach in the analysis. In the system expansion approach, the container system boundaries are expanded to include collection and reprocessing of postconsumer containers, as well as the net virgin material displacement or inputs required, based on the balance between the container system's closed-loop recycled content and closed-loop recycling rate (ISO, 2006b). The types and quantities of materials that are displaced by the recovery and secondary processing of post-consumer container material determine the types and quantities of avoided environmental burdens. Inclusion of recycled content is only modeled in a sensitivity analysis for the single-serve bottle. Recycling allocation is incorporated as a sensitivity analysis for both the single-serve and multi-serve options.

- **Filled bottle transport distance:** A sensitivity analysis is conducted for the multi-serve bottle option varying the transport distance ± 50 miles from the baseline. Both a shorter distance of 25 miles, and a longer distance of 125 miles is modeled for comparison.
- **Bottle water treatment steps:** The baseline analysis models the source of the bottled water as extracted spring water with additional steps of ultrafiltration, ozone and UV treatment (ORDEQ, 2009). Many bottled water brands in the U.S. package spring water, which is from onsite underground formations and is not derived from municipal water treatment. Additionally, water purification steps at the filling plant tend to be less intensive for spring water. An alternative source of purified municipal water is modeled in a sensitivity analysis (Cashman et al., 2014). This sensitivity analysis is conducted for both the single-serve and multi-serve options.
- **Reusable glass washing option:** A sensitivity analysis is conducted assuming the reusable glass for the multi-serve jug option is either hand washed after use or not washed at all.

4. LCA RESULTS

LCA results for this study are provided in a companion Excel results calculator (Appendix B). An image of the selection of input values for the results calculator is depicted in Figure 7. Users can select from available sensitivity analysis parameter values in the green highlighted cells. Section 4.1 through 4.3 highlight analysis findings from generating results with this calculator using the default (i.e., baseline) parameter values. Minimum and maximum impact results are also generated to understand the range of findings. Section 4.4 provides additional sensitivity analysis results, while Section 4.5 provides comparative cost findings.

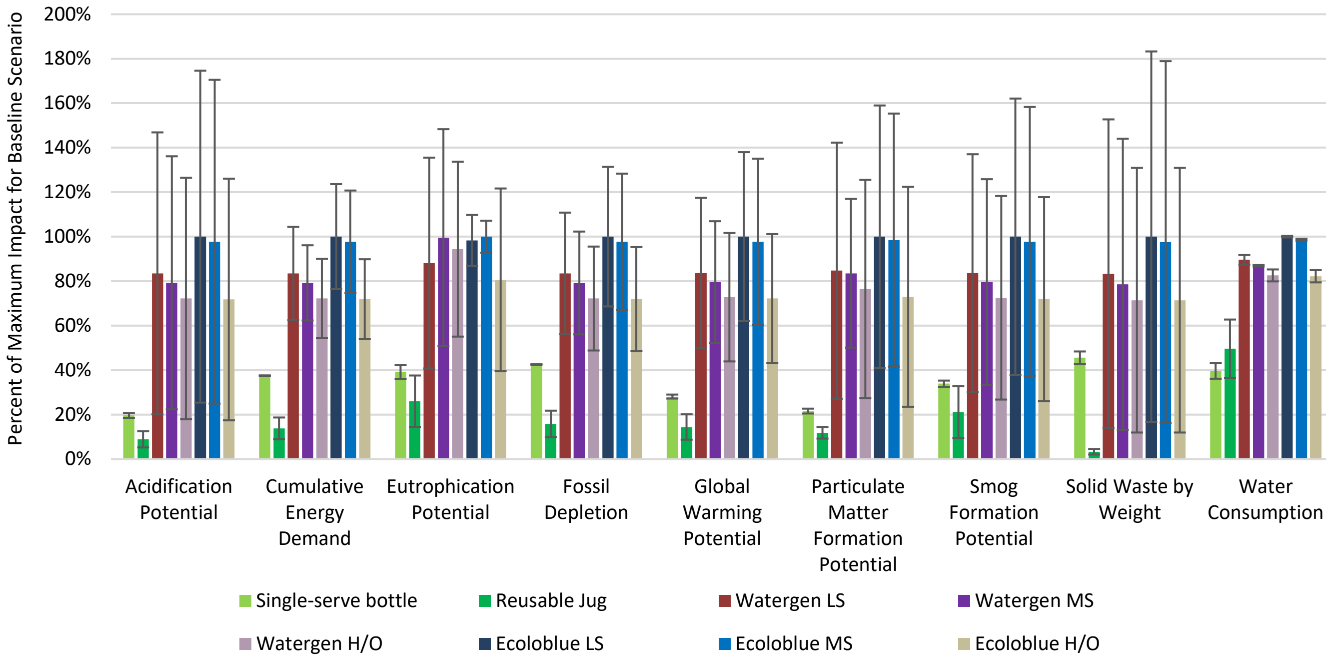
Parameter Description	Select Value	Instructions	Default
Reusable Container Washing Method	Handwash	Select "Handwash" or "No Wash"	Handwash
Jug Transport Distance	Average	Select "Average" if 75 miles, "Minimum" if 25 miles, "Maximum" if 125 miles	Average
Single-serve Bottle Weight	Minimum	Select Minimum (9.3 g) or Maximum (10.9 g). Only lightweight options provided.	Minimum
Single-serve Bottle Recycled Content	None	Select "0%" or "10%"	None
Recycling Allocation Method	Cutoff	Select "Cutoff" or "System Expansion"	Cutoff
Bottled Water Source	Spring Water	Select "Spring Water" or "Treated Municipal Water"	Spring Water
AWG Vendor	WaterGen	Select "WaterGen" or "Ecoloblue"	WaterGen
AWG Water Production	Average	Select "Minimum", "Average", or "Maximum"; Function of relative humidity and temperature	Average
AWG Electrical Grid	Average US	Select "Average US", "RFCW", or "FRCC". RFCW and FRCC are eGRID subregions.	Average US

Figure 7. Input values for the Appendix B results calculator. Available parameter values can be selected from the dropdowns in the green highlighted cells.

4.1 Summary Baseline Comparative Results on an Equivalent Volume of Water Delivered Basis

Figure 8 and Table 9 display the summary baseline LCA results. Table 10 and Table 11 show summary impacts under the maximum and minimum impacts scenarios. The maximum scenario includes treated municipal water for the product (bottled water), handwashing (reusable glass), RFCW electrical grid (AWG operation), maximum bottle weight and transport distance, and virgin content (single-serve bottle). The minimum scenario includes spring water for the product (bottled water), no washing (reusable glass), CAMX electrical grid (AWG operation), minimum bottle weight and transport distance, and ten percent recycled content (single-serve bottle). It is clear from Figure 8 that across all impact categories except water consumption, the multi-serve reusable jug option has the lowest impacts compared to the single-serve bottled water and the two AWG options studied. Water consumption is higher for the multi-serve jug due to water used for the reusable glass handwashing. Figure 8 also reveals that under the *baseline conditions* the AWG systems generally have higher impacts as compared with the bottled water systems. Of the two AWG vendors, Ecoloblue large scale and medium scale units show the highest impacts across all categories in the *baseline scenario*. Only under the *minimum impacts* scenario, impacts including acidification potential, smog formation potential and solid waste by weight are higher for the single-serve bottled water system as compared to the AWGs and the reusable jug (see Table 11). The error bars in Figure 8 show the range of impacts between the scenario with the highest impacts and the scenario with the lowest impacts. The errors are calculated as the average of the two extremes with respect to the maximum of each impact category in the default scenario. The Ecoloblue large and medium scale units also have the longest error bars showing a large variability in the highest and lowest impact scenarios primarily due to the electrical grid used. The scope, range and variability of data points available for medium scale Watergen and Ecoloblue units is also reflected in the length of the error bars.

The home/office scale units of the two vendors perform almost equivalently in terms of assessed impacts.



H/O = home office scale; LS = large scale; MS = medium scale

Figure 8. System comparison of life cycle impacts for large, medium and home/office scale for Watergen and Ecoloblue AWG venders along with the single-serve and multi-serve bottled water systems. Error bars show the range of impacts between the maximum and minimum impact scenarios for all systems as compared to the default scenario.

Table 9. Summary Baseline LCA Results (per Liter Water Delivered)

Impact Category	Unit	Total Impacts Per Liter							
		Single-serve bottle	Reusable Jug	Watergen (Large Scale)	Watergen (Medium Scale)	Watergen (Home/Office Scale)	EcoloBlue (Large Scale)	EcoloBlue (Medium Scale)	EcoloBlue(Home/ Office Scale)
Acidification Potential	*kg SO_2 eq*	5.08E-04	2.30E-04	2.16E-03	2.05E-03	1.87E-03	2.59E-03	2.53E-03	1.86E-03
Cumulative Energy Demand	*MJ*	2.54E+00	9.32E-01	5.64E+00	5.35E+00	4.88E+00	6.75E+00	6.60E+00	4.86E+00
Eutrophication Potential	*kg N eq*	1.83E-05	1.21E-05	4.11E-05	4.64E-05	4.40E-05	4.58E-05	4.66E-05	3.76E-05
Fossil Fuel Depletion	*kg oil eq*	5.40E-02	2.01E-02	1.06E-01	1.01E-01	9.17E-02	1.27E-01	1.24E-01	9.13E-02
Global Warming Potential	*kg CO_2 eq*	1.18E-01	6.06E-02	3.52E-01	3.34E-01	3.06E-01	4.20E-01	4.11E-01	3.03E-01
Particulate Matter Formation Potential	*kg PM2.5 eq*	2.98E-05	1.64E-05	1.17E-04	1.15E-04	1.06E-04	1.38E-04	1.36E-04	1.01E-04

Table 9. Summary Baseline LCA Results (per Liter Water Delivered)

Impact Category	Unit	Total Impacts Per Liter							
		Single-serve bottle	Reusable Jug	Watergen (Large Scale)	Watergen (Medium Scale)	Watergen (Home/Office Scale)	EcoloBlue (Large Scale)	EcoloBlue (Medium Scale)	EcoloBlue(Home/ Office Scale)
Smog Formation Potential	*kg O_3 eq*	7.87E-03	4.91E-03	1.94E-02	1.85E-02	1.69E-02	2.32E-02	2.27E-02	1.67E-02
Solid Waste by Weight	*kg SW eq*	2.18E-02	1.58E-03	3.98E-02	3.75E-02	3.41E-02	4.78E-02	4.66E-02	3.41E-02
Water Consumption	*liter H_2O*	1.62E+00	2.03E+00	3.66E+00	3.55E+00	3.38E+00	4.09E+00	4.03E+00	3.36E+00

Table 10. Summary of Maximum Impact Scenario Results (per Liter Water Delivered)

Impact Category	Unit	Total Impacts Per Liter							
		Single-serve bottle	Reusable Jug	Watergen (Large Scale)	Watergen (Medium Scale)	Watergen (Home/Office Scale)	EcoloBlue (Large Scale)	EcoloBlue (Medium Scale)	EcoloBlue(Home/ Office Scale)
Acidification Potential	*kg SO_2 eq*	5.53E-04	2.84E-04	3.54E-03	3.35E-03	3.05E-03	4.25E-03	4.15E-03	3.04E-03
Cumulative Energy Demand	*MJ*	2.44E+00	1.05E+00	6.33E+00	5.99E+00	5.48E+00	7.59E+00	7.41E+00	5.46E+00
Eutrophication Potential	*kg N eq*	2.07E-05	1.57E-05	5.70E-05	5.96E-05	5.99E-05	6.64E-05	6.60E-05	5.35E-05
Fossil Fuel Depletion	*kg oil eq*	5.14E-02	2.32E-02	1.31E-01	1.24E-01	1.13E-01	1.57E-01	1.53E-01	1.13E-01
Global Warming Potential	*kg CO_2 eq*	1.22E-01	7.20E-02	4.62E-01	4.38E-01	4.01E-01	5.53E-01	5.40E-01	3.99E-01
Particulate Matter Formation Potential	*kg PM2.5 eq*	3.20E-05	1.51E-05	1.82E-04	1.75E-04	1.63E-04	2.17E-04	2.12E-04	1.58E-04
Smog Formation Potential	*kg O3 eq*	8.32E-03	7.01E-03	2.97E-02	2.81E-02	2.57E-02	3.56E-02	3.48E-02	2.56E-02
Solid Waste by Weight	*kg SW eq*	2.43E-02	2.03E-03	6.82E-02	6.43E-02	5.85E-02	8.18E-02	7.99E-02	5.85E-02
Water Consumption	*liter H_2O*	1.91E+00	2.40E+00	2.80E+00	2.74E+00	2.64E+00	3.05E+00	3.02E+00	2.62E+00

Table 11. Summary of Minimum Impact Scenario Results (per Liter Water Delivered)

Impact Category	Unit	Total Impacts Per Liter							
		Single-serve bottle	Reusable Jug	Watergen (Large Scale)	Watergen (Medium Scale)	Watergen (Home/Office Scale)	EcoloBlue (Large Scale)	EcoloBlue (Medium Scale)	EcoloBlue(Home/ Office Scale)
Acidification Potential	*kg SO_2 eq*	4.96E-04	9.52E-05	2.64E-04	4.06E-04	2.48E-04	3.87E-04	3.82E-04	2.33E-04

Table 11. Summary of Minimum Impact Scenario Results (per Liter Water Delivered)

Impact Category	Unit	Total Impacts Per Liter							
		Single-serve bottle	Reusable Jug	Watergen (Large Scale)	Watergen (Medium Scale)	Watergen (Home/Office Scale)	EcoloBlue (Large Scale)	EcoloBlue (Medium Scale)	EcoloBlue(Home/ Office Scale)
Cumulative Energy Demand	*MJ*	2.43E+00	3.88E-01	3.51E+00	3.71E+00	3.06E+00	4.40E+00	4.30E+00	3.04E+00
Eutrophication Potential	*kg N eq*	1.78E-05	4.97E-06	1.28E-05	1.05E-04	2.32E-05	5.57E-05	5.93E-05	1.52E-05
Fossil Fuel Depletion	*kg oil eq*	5.15E-02	8.10E-03	6.16E-02	6.52E-02	5.39E-02	7.73E-02	7.55E-02	5.34E-02
Global Warming Potential	*kg* CO_2 *eq*	1.15E-01	2.41E-02	1.78E-01	2.08E-01	1.59E-01	2.34E-01	2.27E-01	1.55E-01
Particulate Matter Formation Potential	*kg PM2.5 eq*	2.89E-05	7.84E-06	2.27E-05	8.29E-05	2.70E-05	5.38E-05	5.52E-05	2.11E-05
Smog Formation Potential	*kg* O_3 *eq*	7.66E-03	1.58E-03	4.86E-03	6.62E-03	4.44E-03	6.74E-03	6.64E-03	4.27E-03
Solid Waste by Weight	*kg SW eq*	2.16E-02	8.28E-04	1.88E-03	1.77E-03	1.61E-03	2.25E-03	2.20E-03	1.61E-03
Water Consumption	*liter* H_2O	1.62E+00	1.32E+00	2.62E+00	2.71E+00	2.42E+00	3.03E+00	2.98E+00	2.40E+00

4.2 Baseline Results Atmospheric Water Generator

The baseline percent contribution results for the LCA of AWG systems of Watergen and Ecoloblue show higher impacts for all impact categories in the operational stage of the life cycle as compared to two select life cycle stages of manufacturing of the equipment and reusable container washing. Reusable container washing sources water from the AWG, so these impacts are approximately half of AWG operation (assuming half the volume of the reusable glass is used for washing). The operation of the AWG is an energy intensive process and the impacts can be mitigated to some extent by using a low emissions electric grid option (CAMX, see sensitivity analysis for AWG systems). As a comparison between the two vendors of AWG, Ecoloblue has higher overall impacts as compared with Watergen except for eutrophication potential and particulate matter formation potential in the capital equipment stage. This is due to the longer lifetime estimated for the Ecoloblue systems. The life cycle stages not shown here (transportation to point of use and disposal) have negligible impacts on the LCA results.

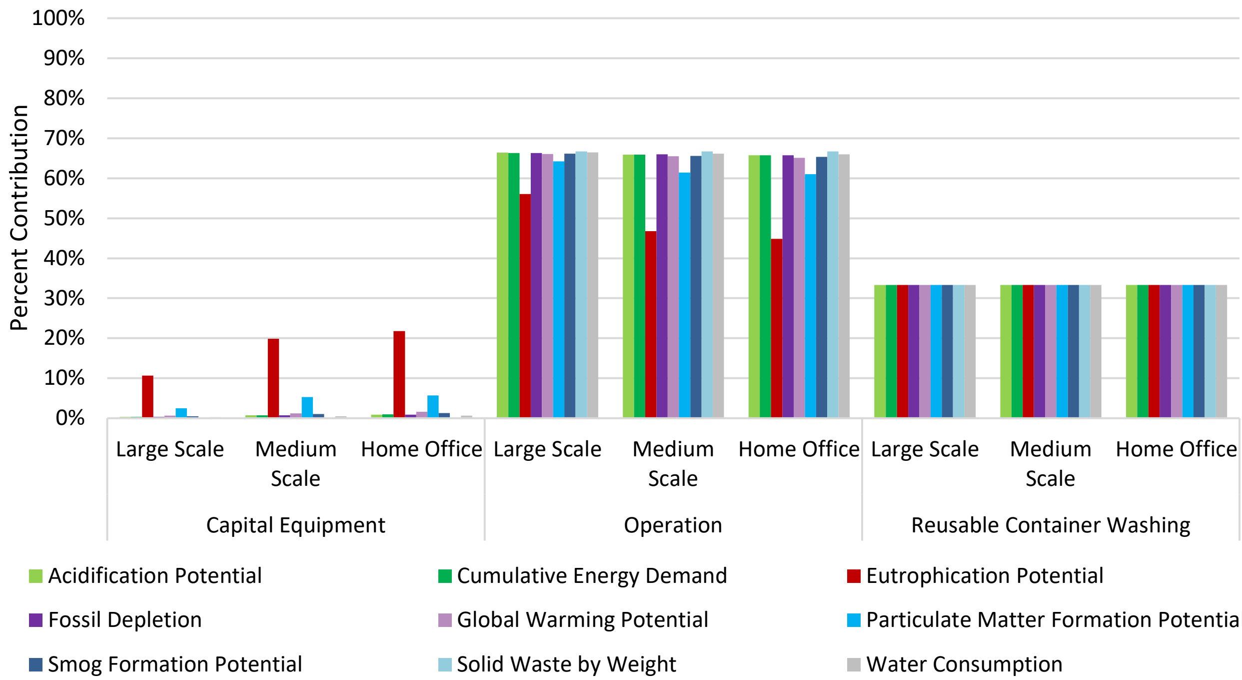


Figure 9. Watergen percent contribution to life cycle stage by impact category.

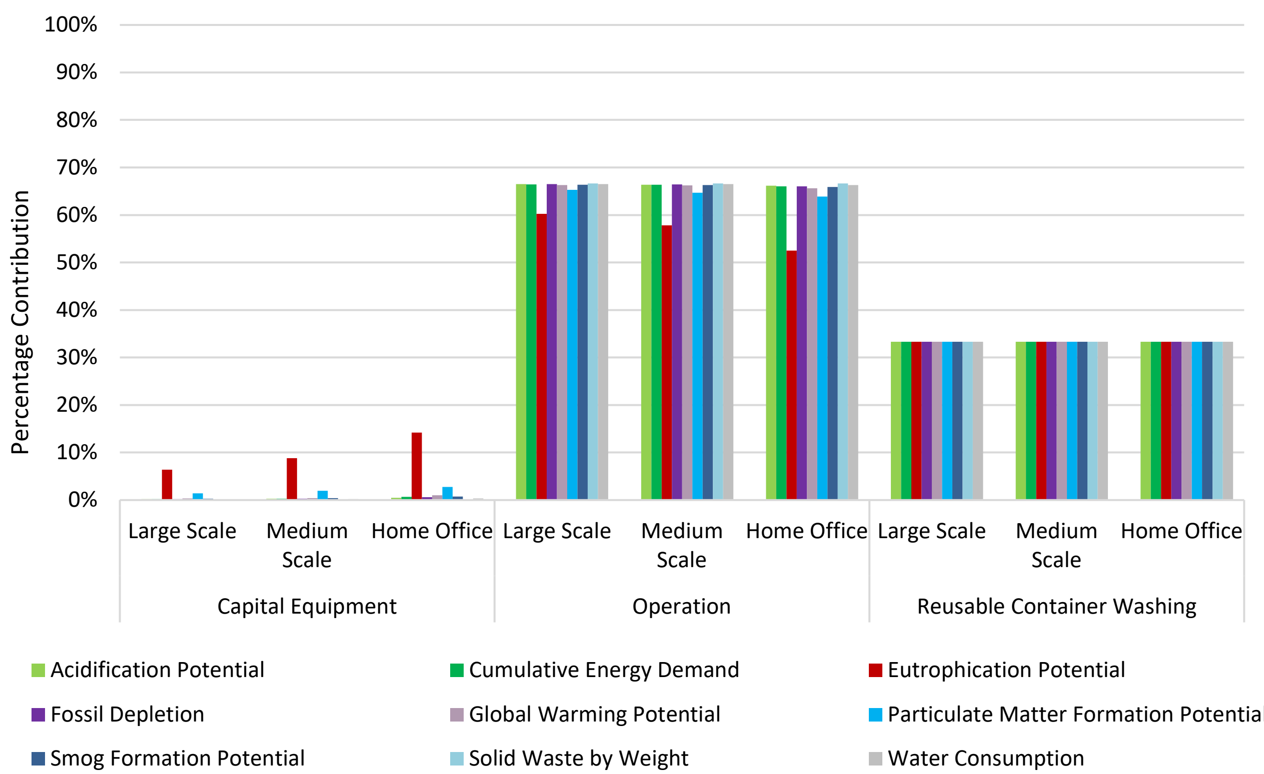


Figure 10. Ecoloblue percent contribution to life cycle stage by impact category.

4.3 Baseline Results Bottled Water

For single-serve bottles, raw material production has the highest contribution to most impact categories especially fossil fuel depletion and cumulative energy demand (Table 12). The end of life contributes most to the solid waste generated by weight as 68.7 percent of the bottles are disposed, with 82.2 percent of disposed packaging being landfilled in the U.S. (U.S. EPA, 2016). For HOD, transportation of filled jugs to the user and transportation of empty jugs from the user contributes most to impact categories including smog formation potential, global warming potential and fossil fuel depletion (Table 13). Water treatment shows high water consumption for both systems since the product water is incorporated in this stage.

Table 12. Single-serve Bottled Water Percent Contribution to Life Cycle Stage by Impact Category

Category	Raw Material Production	Conversion	Water Treatment	Filling	Transportation to Retail	Closure Life Cycle	Label Life Cycle	Secondary Packaging Life Cycle	Bottle End-of-Life
Acidification Potential	39%	36%	0%	1%	12%	6%	3%	4%	0%
Cumulative Energy Demand	51%	16%	0%	0%	8%	9%	4%	11%	0%
Eutrophication Potential	49%	20%	3%	0%	18%	4%	2%	3%	1%
Fossil Fuel Depletion	53%	15%	0%	0%	9%	8%	4%	10%	0%
Global Warming Potential	43%	22%	0%	0%	12%	7%	3%	9%	4%
Particulate Matter Formation Potential	45%	31%	0%	1%	9%	6%	3%	5%	1%
Smog Formation Potential	40%	26%	0%	0%	22%	5%	2%	4%	1%
Solid Waste by Weight	12%	13%	0%	0%	1%	8%	6%	11%	49%
Water Consumption	11%	10%	72%	0%	2%	2%	1%	2%	0%

Table 13. Multi-Serve Bottled Water Percent Contribution to Life Cycle Stage by Impact Category

Category	Raw Material Production	Conversion	Water Treatment	Filling	Transportation to and from User	Closure Life Cycle	Reusable Container Washing	Jug Washing	Jug Recycling
Acidification Potential	11%	4%	0%	1%	38%	5%	33%	7%	0%
Cumulative Energy Demand	12%	3%	0%	1%	38%	9%	33%	5%	0%

Table 13. Multi-Serve Bottled Water Percent Contribution to Life Cycle Stage by Impact Category

Category	Raw Material Production	Conversion	Water Treatment	Filling	Transportation to and from User	Closure Life Cycle	Reusable Container Washing	Jug Washing	Jug Recycling
Eutrophication Potential	12%	1%	5%	0%	38%	2%	33%	8%	0%
Fossil Fuel Depletion	12%	2%	0%	1%	40%	8%	33%	4%	0%
Global Warming Potential	14%	3%	0%	1%	40%	5%	33%	4%	0%
Particulate Matter Formation Potential	25%	3%	0%	1%	28%	4%	33%	5%	0%
Smog Formation Potential	7%	2%	0%	1%	52%	3%	33%	3%	0%
Solid Waste by Weight	0%	11%	1%	3%	21%	11%	33%	18%	0%
Water Consumption	1%	0%	58%	0%	2%	1%	33%	5%	0%

4.4 Sensitivity Analysis Results

This section covers three sensitivity analyses for the AWG systems LCA and four sensitivity analyses for the bottled water LCA:

Sensitivity Analyses for AWG Systems:

1. Variation across four electrical grid mix options
2. Reusable container washing method
3. Water production

Sensitivity Analyses for Bottled Water Systems:

1. Weight options for 16.9 oz bottle (with and without recycled content)
2. Variation in transport distances for re-usable jug
3. Recycling allocation method (system expansion versus cut-off)
4. Bottled water source (spring water vs. treated municipal water)

4.4.1 Sensitivity Analyses for AWG Systems

4.4.1.1 Variation across four grid mix options

This sensitivity analysis includes four electrical grid mix options in order to compare the effect of using a variety of electrical grids to represent a variety in locations of use and a range of resource mixes. We analyzed the impacts of using four eGRID subregion options: Average U.S. (baseline), RFCW (maximum impact option), FRCC and CAMX (low impact option) to operate the AWGs at their average water production volumes per day. This sensitivity analysis highlights the variation in impacts for all scales in the operational stage of their lifecycles. The impacts are calculated on per day bases. Table 14 shows the electricity impacts per kWh of electricity derived from each of the eGRID subregion options. RFCW has the highest cumulative energy demand and global warming potential due to high coal and nuclear resource percentage, whereas, CAMX has the highest water consumption due to high energy contribution from hydropower because evaporative losses from establishment of dams is included. The two AWG product systems were modeled to operate under the four eGRID subregions and the daily impacts of the large- and medium-scale units on select categories are shown in Figure 11. The impacts are from the different volumes of water produced and are generally higher for the Ecoloblue AWGs for the large and medium scales units due to EcoloBlue reporting higher kWh/L values for operation. The results are less significant from the small scale AWGs, thus, not shown. The RFCW option has the highest cumulative energy demand and global warming potential whereas global warming potential and cumulative energy demand are lowest under the CAMX option, although it has the highest water consumption of all four options due to the prevalence of hydro-based electricity in this option.

Table 14. Regional Electricity Impacts per kWh

Impact category	Unit	US Average	RFCW	FRCC	CAMX
Acidification Potential	kg SO_2 eq	4.09E-03	6.73E-03	2.33E-03	7.32E-04
Cumulative Energy Demand	MJ eq	1.07E+01	1.20E+01	1.14E+01	9.96E+00
Eutrophication Potential	kg N eq	6.57E-05	1.01E-04	5.28E-05	2.40E-05
Fossil Fuel Depletion	kg oil eq	2.01E-01	2.49E-01	2.62E-01	1.75E-01
Global Warming Potential	kg CO_2 eq	6.63E-01	8.76E-01	7.82E-01	5.02E-01
Particulate Matter Formation Potential	kg PM2.5 eq	2.15E-04	3.41E-04	1.71E-04	5.65E-05
Smog Formation Potential	kg O_3 eq	3.67E-02	5.64E-02	2.94E-02	1.36E-02
Solid Waste by Weight	kg	7.58E-02	1.30E-01	3.15E-02	5.36E-03
Water Consumption	liter H2O	4.10E+00	2.46E+00	5.63E-01	4.61E+00

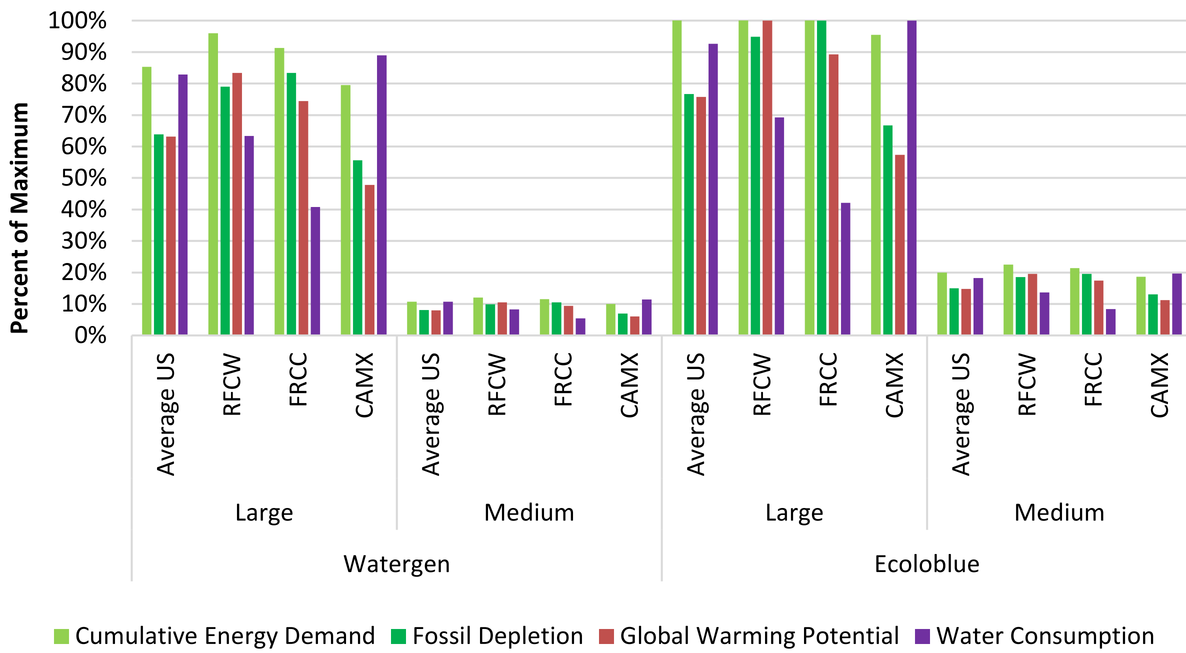


Figure 11. Impacts per day of large and medium scale AWG operation with Average U.S., RFCW, FRCC and CAMX eGRID locations shown as percent of maximum for select impact categories.

4.4.1.2 Reusable Container Washing Method

For the AWG systems, impacts decrease for all categories approximately 33% when shifting from handwashing of the reusable container to no washing. Impacts are affected universally, as the water used for washing in an emergency situation is assumed to be generated by the AWG unit.

4.4.1.3 Water Produced per Day

This sensitivity analysis compares the impacts associated with maximum daily water production and minimum daily water production. Figure 12 shows the impacts associated with the average volume of water produced daily by the AWGs for all three scales and both vendors, as a percent of maximum impact in each impact category. The error bars show the variability in impacts associated with the maximum and minimum water produced by each AWG. The errors are calculated as the average of the maximum and minimum impacts for each impact category for each AWG vendor and scale. The highest variability is seen for Watergen medium scale and EcoloBlue large and medium scale AWGs particularly for the cumulative energy demand, water consumption, and global warming potential. The vendors provided detailed performance data for the daily volume produced by these three AWGs, which is why the variability in impacts is larger as compared to the other three AWGs for which the detailed performance data was not available. Because operational data is a static kWh usage per L, the actual electricity for operation does not vary on a functional unit basis. The difference in the results shown here are, therefore, primarily related to capital equipment requirements after standardization over total AWG lifetime water production.

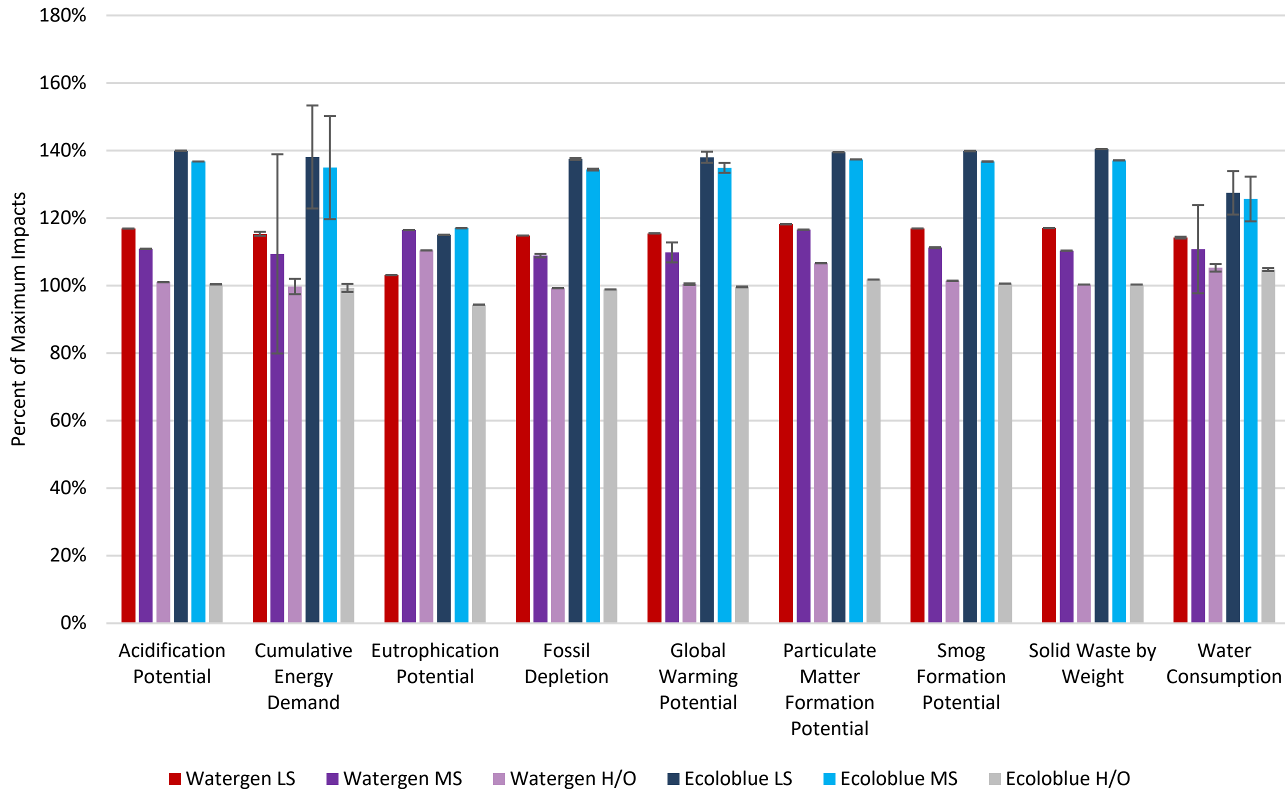


Figure 12. Percent of maximum impacts of average daily water produced with error bars showing the range of impacts associated with maximum and minimum daily water produced.

4.4.2 Sensitivity Analyses for Bottled Water Systems

4.4.2.1 Weight Options for 16.9 oz Single-serve Bottle (with and without Recycled Content)

Two lightweight bottles were assessed in this sensitivity analysis, each using virgin PET and up to 10% recycled content, respectively. The default lightweight 16.9 oz bottle weights 9.3 grams (minimum) and has no recycled content. The sensitivity analysis includes comparison with a 9.3 gram bottle with 10% recycled content, a 10.9 gram bottle (maximum) made with virgin PET and a 10.9 gram bottle with 10% recycled content. The percentage change in impacts from switching from the default weight and recycled content to the three options discussed is shown in Figure 13. Adding recycled content further reduces the impacts for the 9.3 gram bottle system, however increasing the weight of the bottle even slightly increases impacts across all impact categories. Adding 10% recycled content still makes the reusable jug a desirable alternative except in the case of handwashing whereas the reusable jug has higher water consumption as compared with the single-serve bottle. Including recycled contents in the bottles reduced greenhouse gas emissions and energy demanded as compared to manufacturing bottles from virgin PET. As compared with the AWGs systems, the impacts associated with all four scenarios of the single-serve bottle (weight and recycled content) are higher than those of AWG of both vendors for acidification potential, eutrophication potential, particulate matter formation, smog formation, and solid waste by weight impact categories if the AWGs are using CAMX energy mix and producing any (minimum, maximum or average) daily volume of water. Using a reduced emissions energy mix option does make AWG a lower impact alternative to single-serve bottled water for select impact categories (see Appendix B for the results).

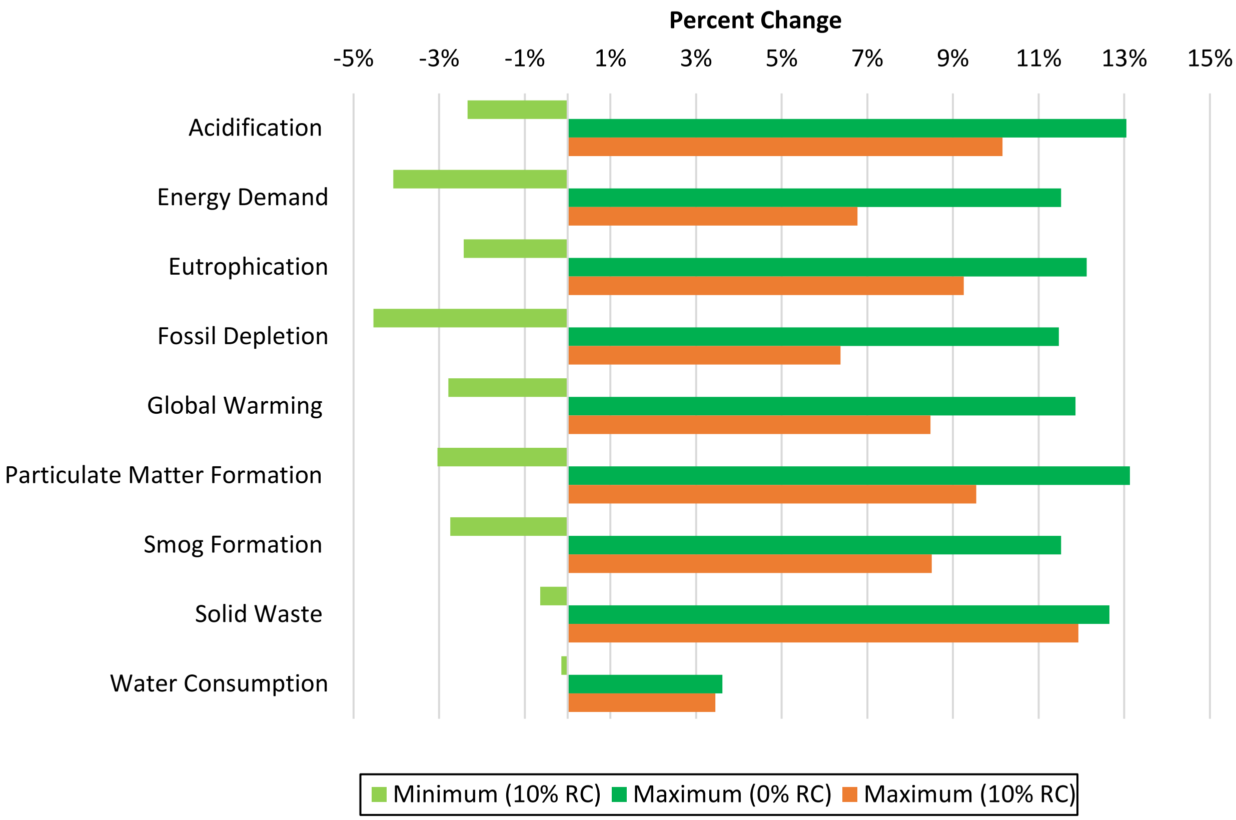


Figure 13. Sensitivity to bottle weights of 9.3g (minimum) and 10.9g (maximum) and recycled contents (RC) of 0 percent and 10 percent.

4.4.2.2 Variation in Transport Distances for Reusable Jug

In the baseline analysis, the use of diesel-based transportation of reusable bottled water shows high impacts across all impact categories especially smog formation potential, global warming potential and fossil fuel depletion, so we carried out a sensitivity analysis for the transportation distance. The default assumption is 75 miles and we studied the impacts of a longer (maximum) distance of 125 miles and a shorter (minimum) distance of 25 miles. Figure 14 shows the percentage change in impacts if a minimum or maximum distance were chosen instead of the default 75 miles. The figure highlights that impacts across all impact categories increase if the distance is increased and decrease with a shorter distance travelled to and from the users. These impacts are higher for transportation of a filled jug from the plant to the user as opposed to the transportation of empty jugs from user to the plant. When comparing results of this sensitivity analysis to the AWG LCA results, the overall impacts of the reusable jug with maximum transportation distance scenario remain low for all categories except for smog formation potential under the CAMX grid mix scenario and water consumption under the FRCC scenario for AWGs producing maximum daily volume of water (see Appendix B for the results).

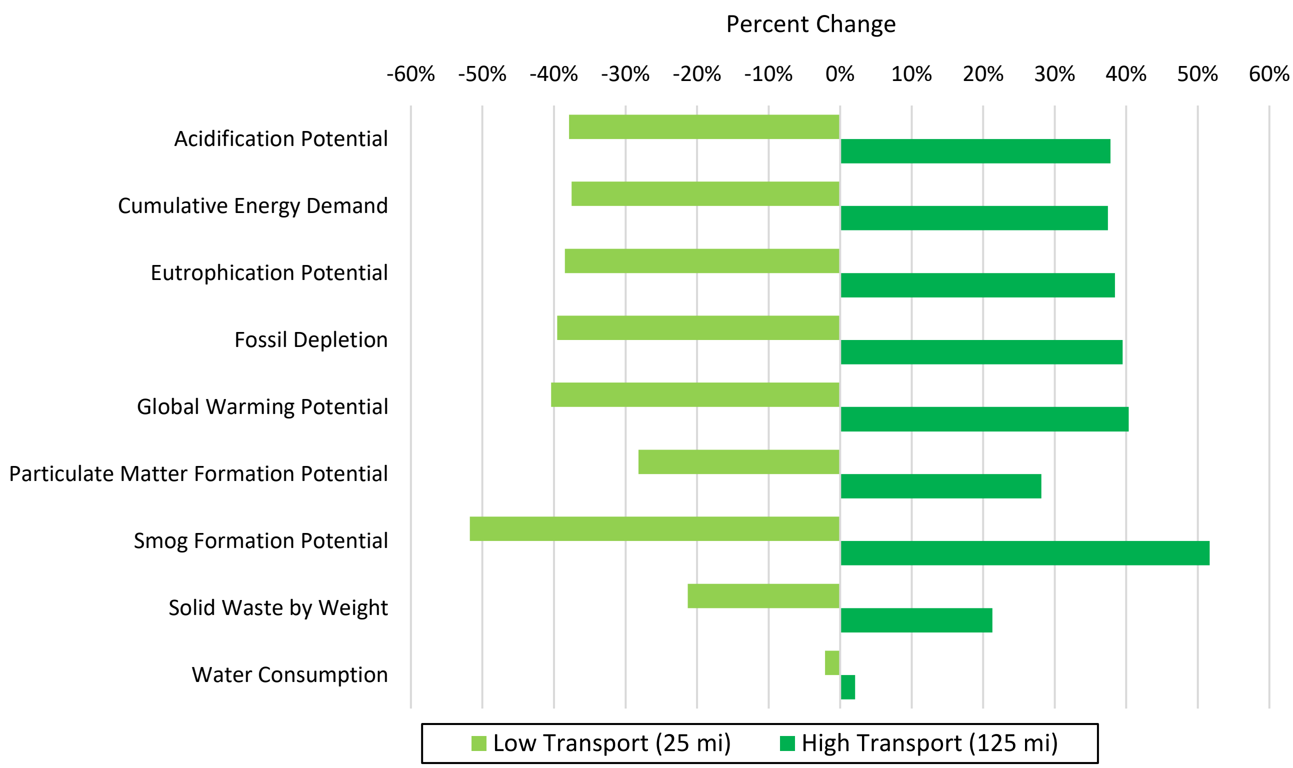


Figure 14. Sensitivity to transportation distance of reusable jug to and from the user.

4.4.2.3 Recycling Allocation Method (System Expansion versus Cut-off)

Using system expansion to include recycling of bottles instead of the cut-off method provides significant reduction in cumulative energy demand and global warming potential, but an increase in water consumption for both the single-serve and multi-serve bottle system as highlighted in Table 15. System expansion incorporates avoided virgin product credit where the product (bottle) is given "credit" for the potential recycled material included, which displaces the need for virgin PET production. Water consumption is higher because system expansion also incorporates recycling burdens at end of life. The washing of the flake during the recycling processes, in order to manufacture a product that is able to displace virgin material, is a water intensive process.

Table 15. Sensitivity to Recycling Allocation Method for the Single-Serve and Multi-serve Bottled Water Systems for Select Impact Categories when Shifting to System Expansion (per Liter Water Delivered)

Impact category	Units	Cut-off	System Expansion		Cut-off	System Expansion	
		Single-serve bottle	*Single-serve bottle*	*% change*	*Reusable Jug*	*Reusable Jug*	*% change*
Cumulative Energy Demand	**MJ**	2.54E+00	2.19E+00	-13.58%	9.32E-01	6.90E-01	-25.93%
Global Warming Potential	**kg CO_2 eq**	1.18E-01	1.09E-01	-7.55%	6.06E-02	4.68E-02	-22.72%
Water Consumption	**liter H_2O**	1.62E+00	1.62E+00	0.10%	2.01E+00	1.83E+00	-9.40%

4.4.2.4 Bottled Water Source (Spring Water vs. Treated Municipal Water)

The percent change in select impacts from using treated municipal water instead of spring water is highlighted in Table 16 for both bottled water systems. The impacts of using treated municipal water are higher for both systems for select impact categories of cumulative energy demand, global warming potential and water consumption. Water consumption is higher because treated municipal water has significant losses during distribution (in piping system from drinking water treatment plant to filling plant) and the treatment process is more energy intensive than the treatments carried out for using spring water.

Table 16. Sensitivity to the Source of Water for the Single-serve and Multi-serve Bottled Water Systems for Select Impact Categories when Shifting to Municipal Water Treatment

Impact category	Single-serve bottle	Reusable Jug
	% change	% change
Cumulative Energy Demand	0.32%	1.29%
Global Warming Potential	0.43%	1.25%
Water Consumption	14.01%	16.82%

4.5 Price Comparison between Systems

This section calculates a standardized price for both the AWG and the bottled water per liter bases shown in Table 17. The standardized price per liter of water for AWG includes a net present cost calculation of the unit price of the AWG unit and the maintenance and energy costs over the lifetime of the AWGs (ten years for Watergen units and 20 years for EcoloBlue units). This discounted cost is then used to calculate the per liter cost based on the average total volume of water produced by the AWG over its lifetime. The unit and maintenance costs are provided by the vendors and the annual discounted price of electricity is calculated based on the U.S. average price of electricity (10.82 cents per kWh, EIA 2018). An AWG unit can be used for multiple long-term emergency situations and locations over its lifetime but that does not affect its initial unit price, annual maintenance cost and the price of electricity. It can be safely assumed that the per liter cost of water produced by an AWG will remain the same no matter where it is being used in the country. If the AWG unit remains idle for a long period of time that can reduce its operational cost over its lifetime but the maintenance would have to be carried out regardless of the duration of use.

The standardized cost for bottled water is based on the unit price of a 24 pack (12 liters) for the single-serve bottle selected for the Poland Spring brand and the Poland Spring 5 gallon jug (18.9 liters). The monthly flat rate delivery charge is also included in the per liter cost of the reusable jug, but it is based on the assumption that 4 jugs are delivered in a month (this amount varies by household). In addition, 54.5 cents per mile of transporting the single-serve bottle was added to the per liter cost based on the US government standard mileage reimbursement rate (IRS, 2018). It is understood that during a long-term emergency situation the bottled water is typically provided by the local or state government and the price is not the same as that paid by consumers in a grocery store. The cost analysis is based on the grocery store and vendor prices as data is not available for the prices the government is charged in emergency situations.

While AWGs require significant upfront capital compared to bottled water, costs compared to bottled water are lower when standardized over the useful life of the AWG unit.

Table 17. Standardized Costs per Liter of Water

Product	Type	Unit cost ($)	Annual maintenance cost ($)	AWG (kWh/L)	Electricity Cost per Liter*	Total cost per liter ($)
AWG – Watergen	Large	115,000	7,866	0.35	0.04	0.09
AWG – Watergen	Medium	55,000	2,500	0.33	0.04	0.14
AWG – Watergen	Home/Office	1,250	288	0.3	0.03	0.13
AWG – Ecoloblue	Large	159,700	3,767	0.42	0.05	0.06
AWG – Ecoloblue	Medium	30,750	870	0.41	0.04	0.06
AWG – Ecoloblue	Home/Office	799	288	0.3	0.03	0.07
Bottled water	Single-serve†	4.49	-	-		0.38§
Bottle water	Multi-serve†	7.49	6.95‡	-		0.49

*U.S. average price of electricity for commercial use in June 2018 was 10.82 cents per kWh (EIA, 2018)
§Includes water transportation cost based on the U.S. government standard mileage reimbursement rate (IRS, 2018)
†Price of single-serve bottles is calculated for a 24 pack/12L and price of multi-serve jug is for 5gallons/18.9L
‡ Monthly delivery cost which is a flat rate, we assumed monthly consumption of 4 jugs

5. Conclusions and Next Steps

This section presents some conclusions from the study for bottled water systems in comparison with the atmospheric water generators as two emergency response options for potable drinking water. Generally, the environmental impact results show that bottled water, specifically reusable 5-gallon jugs, have lower environmental impacts as source of potable water in emergency situations compared to AWGs. Conversely, AWG costs may be lower than bottled water when considering costs over the entire lifetime of the unit. Some of the key results are listed below:

- The energy requirements for operation of AWGs dominate life cycle impacts.
  - Notable reductions in AWG impacts are achievable through utilization of low impact electrical grids.
  - This study did not model a fully renewable electrical option. This could be explored to reduce AWG environmental impacts.
- Raw material production and conversion stages dominate life cycle impacts for the single-serve bottle system.
  - Use of a lightweight PET bottle with recycled content improves the overall performance of these single-serve systems.
  - Lightweighting bottles reduces impacts across all life cycle stages including raw material production, conversion, transport, and disposal at end-of-life.
  - This study only considered truck transport of the single-serve bottles (100 mi from filler to use point). Transport could have a higher impact if bottles are required to be sent by a different mode of transport, such as a plane, to emergency response locations.
- Transportation of bottle to and from the user is significant across several impact categories for the HOD jug system. The HOD jug system is also sensitive to the washing method used for the water delivery glass.
- The cost per liter of water from the AWG system is lower compared to the bottled water system as the costs have been calculated over the lifetime of the AWG units.
- Addition of short-term weather-related emergency situations such as drought, tornados and hurricanes may be considered in future project steps.
- AWG alternatives with connectivity to off grid options such as solar or wind power sources may be studied and compared with bottled water systems in future project steps.
- Use of aviation to provide bottled water in remote and inaccessible locations may be added as a scenario in future analyses.

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APPENDIX A
AWG INVENTORY DATA COMPILED

Appendix A: AWG Inventory Data Compiled

All the data provided by the vendors and that was used in setting up the LCA models is compiled and provided as a separate excel file: **"AppendixA-AWG_BottledWaterDatav4_12.19.18.xlsx"**.

APPENDIX B
LIFE CYCLE RESULTS CALCULATOR

Appendix B: Life Cycle Results Calculator

A companion dynamic LCA Excel results calculator is provided to run combinations of the parameter values assessed in this study. This is in a separate file named "**AppendixB-Results_Template_AWGBottledWaterv4_12.19.18.xlsx**".