Better than bottled water? - Energy and Climate Change Impacts of On-The-Go Drinking Water Stations

Tamar Makov[a*], Grégoire Meylan[b], Jon T. Powell[c], Alon Shepon[d]

[a] Yale University, School of Forestry & Environmental Studies

[b] ETH Zurich, Department of Environmental Systems Science

[c] Yale University, Department of Chemical & Environmental Engineering

[d] Weizmann Institute of Science, Department of Plant and Environmental Science

Submitted to *Resources, Conservation and Recycling*

---

[*] Corresponding author. [a] Center for Industrial Ecology, 195 Prospect Street, New Haven, CT 06511, USA; Tel.: +1 203.436.4421; e-mail: tamar.makov@yale.edu

ABSTRACT

Growing consumption of single-use bottled water has received criticism due to potentially adverse environmental outcomes. Networks of public-sphere water delivery stations have been proposed as a sustainable alternative for water consumption on-the-go, yet the life-cycle impacts of such stations are poorly understood. Here we evaluate the potential energy demand and climate change impacts of water delivered from a filtered water refill station under various consumption scenarios and provide a comparison to published results for bottled water. Using a hybrid life-cycle analysis framework employing physical and economic data, we model the water station's performance in four locations: Tel-Aviv, Israel; Miami Beach, Florida, USA; London, UK; and Shanghai, China. We find that the climate change impact of the station is two to six times lower than those of bottled water and that use phase electricity is the most influential factor in determining the station's environmental impact. We provide additional observations related to scaling up such a system and recommendations to realize further gains in eco-efficiency.

Keywords: LCA, bottled water, decentralized water systems, water station, water fountain

1 INTRODUCTION

In the past decade, sales of bottled water and per-capita bottled water use in the US have grown substantially, reaching 38 billion liters in 2013, with the majority consisting of single-serve polyethylene terephthalate (PET) bottles (Beverage Marketing Corporation, 2014). The proliferation of bottled water has raised multiple concerns, ranging from water body pollution from discarded containers (Jambeck et al. , 2015) to the energy use and greenhouse gas (GHG) emissions associated with bottle production, transport, and refrigeration (Grady and Younos, 2012). While in developing countries, people are often forced to rely on packaged water because other alternatives for safe water consumption are scarce (Unicef and Organization, 2014), in the developed world, people usually have the luxury of choosing between tap and bottled water.

Various tactics have been deployed to curb bottled water consumption to reduce potential environmental impacts, including awareness campaigns and outreach programs or even bans on bottled water (Nick, 2010, Vince et al. , 2008, Wendy, 2010). However, these strategies neglect to address some key factors behind bottled water's popularity. For example, municipal water contamination issues, such as the recent incident in Flint MI, increase public concern regarding the health and safety of tap water (Ganim and Tran, 2016). Additionally, bottled water is perceived as having superior taste and quality compared to tap water (Beckman, 2014, Hu et al. , 2011). Finally, in most cases, bottled water is easily accessible and convenient for consumption, particularly in public spheres where infrastructure enabling access to municipal water may be limited or not routinely maintained.

To better address consumer demand, municipalities worldwide have planned networks of water stations, with some offering filtered and even sparkling water (e.g., San Francisco, California; Bundanoon, Australia). Such water delivery networks are thought to be 'greener' than bottled water by virtue of being a single-use bottled water alternative, but this conclusion lacks a strong empirical basis. Because water refill stations require infrastructure development and additional energy and material inputs for routine operations and maintenance, their full life cycle impacts must be examined to enable a comparison with bottled water. To date, most analyses of environmental impacts of bottled water consumption focus on comparing bottled and household tap water (Barrios et al. , 2008, Botto et al. , 2011, Daniels and Popkin, 2010, Dettling et al. , 2010, Dettore, 2009, Franklin Associates, 2009, Friedrich, 2002, Friedrich et al. , 2009a, b, Jungbluth, 2006, Nessi et al. , 2012, Parker et al. , 2009, Tarantini and Ferri, 2003, Vince, Aoustin, 2008) with only few studies focusing on other public-sphere water supply alternatives such as water fountains or refill stations (Nessi, Rigamonti, 2012, Torretta, 2013).

The growing concerns with bottled water, coupled with the dearth of environmental performance data for the drinking water station alternative, warrant further examination to facilitate private- and public-sector decision making and systematically evaluate respective environmental claims. The objectives of this study are twofold: first, we evaluate the cumulative energy demand and potential climate change impacts of filtered water delivered form a public-sphere water refill station using a hybrid life cycle (LCA) approach. We model the performance of a commercially-available (Woosh) filtered water station's in several locations under different consumption scenarios. To explore the influence of the various model components and sources of uncertainty, we perform a sensitivity analysis to isolate the factors that most substantially impact our results (see section 4.2). Next, we compare the Climate Change (CC) impact of water delivery from the examined station to an average of bottled water delivery systems as calculated by Fantin et al. (2014). We conclude by discussing the impacts of scaling up consumption of water from Woosh stations.

2 CASE STUDY: THE WOOSH SATTION

The Woosh water station provides chilled or room temperature water for refill on-the-go, with an option to rinse and sanitize the drinking container prior to filling. The water (drawn directly form the municipal water system), is filtered and treated by ozone, and then chilled. Consumers control the station via a touch screen that presents filling volume options (150 mL-1000 mL) and the container rinsing option (bottles are first rinsed with ozone and then with filtered water). Excess water (form spillage or rinsing) is collected through the drain and re-enters the station's water filtration and treatment cycle. For payment, consumers can either register with the company and pay using a pre-paid chip or use a credit card. The consumer cost varies depending on infrastructure and operational costs, but for example, in Miami-Beach Florida, refill rates range from \$0.35-\$0.8 depending on volume, with local residence entitled to up to 30% discount (City of Miami Beach., 2016).

3 MATERIALS AND METHODS

3.1 Goal and scope

We use LCA to evaluate the environmental performance of water delivery from a water filtration station located in a public area. The energy demand and global warming impact of placing the station in four locations are quantified: Tel-Aviv, Israel; Miami-Beach, Florida, USA; London, UK; and Shanghai, China. These locations were principally chosen to model variable electricity generation mixes.

Previous studies have shown that consumer behaviour during the use phase could significantly impact results of LCAs (Polizzi di Sorrentino et al. , 2016). However, given the emergent nature of the drinking water stations predicting exact consumer usage patterns is challenging. Thus, to account for a range of potential water consumption patterns at the Woosh station, multiple scenarios were modeled. First, daily volumetric water consumption was varied from 40 to 150 L/day in 5 liter increments. Second, scenarios with cooled (7-12 °C) and room temperature water were examined. The combination of these two factors is expected to cover the reasonable range of consumer use.

The wide range and incremental nature of the scenarios modeled helps reveal the conditions under which eco-efficiency are optimized.

3.1.1 Functional unit and system boundaries

We define the functional unit as 1L of water delivered to the consumer in each of the four modeled locations. Our analysis includes a cradle to grave assessment of a Woosh water station (from raw material acquisition to end of life, see

Figure 1a), including production, transportation, assembly, transport to final destination, installation, use phase requirements, (i.e., routine maintenance, water and electricity consumption, and part replacements), and end-of-life (EoL) management.

Consumers in all scenarios are assumed to already have a refillable drinking container, and a single container type was selected for analysis. Although reusable drinking containers are available on the market in various sizes and materials of construction, we assumed the container to be a 600 mL aluminum container, which was found to have the greatest environmental impacts in a study comparing various containers (Franklin Associates (2009). In addition to energy and GHG related to production, transport and EoL (as adopted from (Franklin Associates (2009), we also include resources required for washing the reusable container (water and energy). As the water stations are intended to deliver water to consumers 'on-the-go', it is assumed that no special consumer transport is required to reach the refill station.

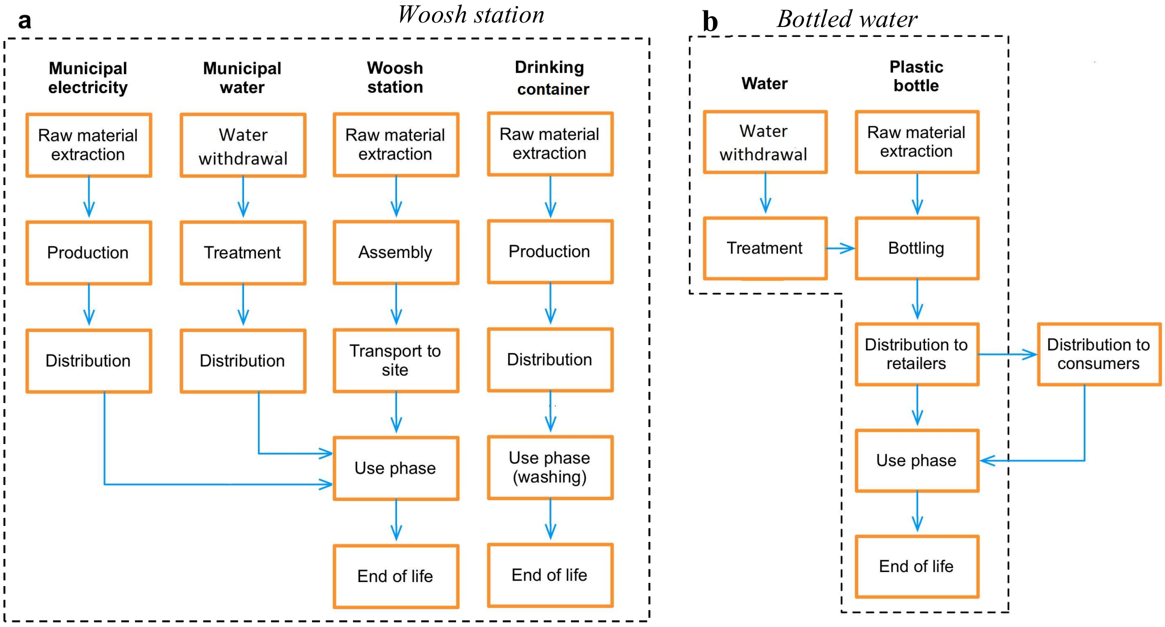


Figure 1: System boundaries of the (a) Woosh station and (b) bottled water.

3.1.2 Modeling framework

Process-based LCA is a method to quantify the entire life cycle environmental impacts of various products, systems or services from cradle to grave and accounts for all inputs required for production, assembly, transportation, use, maintenance, and disposal/treatment and EoL. LCA is composed of four general steps: goal and scope, inventory analysis, impact assessment and interpretation. Environmental input-output (EIO) LCA consists of an economy-wide matrix that allocates environmental impacts (e.g. resource use, air emissions, waste production, etc.) in proportion to economic activity. The impacts of any product or service in the economy are determined by summing all costs related to its direct and indirect inputs throughout the supply chain (Hendrickson et al. , 1998, Joshi, 1999, Matthews and Small, 2000).

In cases where process-based data for major components of the water station used was unavailable, we relied on monetary data to estimate environmental impacts, augmenting process-based LCA with EIO-based LCA (Bilec et al. , 2006). As such, our analysis here is a hybrid LCA, which combines data from several sources to reach the final goal of the assessment.

3.2 Life cycle inventory

We first describe the main data sources and databases used to set up the life cycle inventory for providing 1L of water to the consumer and then continue to give a brief description of the different life stages. We close this section by elaborating on the electricity and municipal water of the different locations modeled. Table 2 summarizes the LCI data for the Woosh station's production and Table 3 summarizes the LCI data for the use and EoL phases at the various modelled locations.

3.2.1 Data sources and databases for the life cycle of a Woosh station

Inventory data for the production and use phase (including part replacement and maintenance) for the water station were collected from the Woosh Company in a series of interviews and e-mail correspondence between May and September 2013. The main data sources include system drawings, technical specifications, photos and a detailed inventory list. The inventory list contained key data on the water station parts and components including material weight and composition, life span, and specific manufacturing locations.

The hybrid LCA model including both process and EIO inventory data was built using SimaPro 8.1 software. Average European values (RER) of the ecoinvent database (v. 2.2) were used as proxies for the assembly of the Woosh station in absence of specific data. In our model we use 2002 EIO tables for the US by converting current costs into 2002 US$. We base our calculations on the US data even though some components are produced in China, since the US-EIO models are considered more detailed and reliable than those currently available for the Chinese economy (Murray et al. , 2008).

3.2.2 Production

The station's parts and components are manufactured in various locations globally (China, Taiwan, the EU, the US, and Israel). It is assumed that they are then shipped to the Woosh factory in Petach Tikva Israel (via the port of Haifa) for partial assembly. Once partial assembly is completed, the station is transported to its final destination where it is installed on top of a concrete foundation, and connected to the municipal water and electricity systems on site (see Figure SI-1 for a photo of the Woosh station and dimensional specifications). Our model assumed that all long hall domestic transport (over 100km) was done by rail, domestic short hall transport was done by lorry, and international transport by container ship to the closest industrial harbour.

3.2.3 Part replacement and maintenance

The life span of each component of the Woosh station was estimated based on the official producer declarations. It is assumed that parts replacement occurs at these intervals and that all parts are replaced by newly-produced ones. The maximum life span of the station as a whole (and subsequently all the more durable components) is assumed to be 10 years. See Table 2 for a detailed summary of all components and parts.

Based on data collected from the pilot period in Tel Aviv, a technician visits each station once every two weeks. Even though the technician could potentially service more than one location per trip, it is assumed that every trip covers one station only.

3.2.4 Use-phase electricity and water

Use-phase electricity consumption was estimated based on data from a power consumption test conducted in September 2013 simulating extreme conditions (i.e. high outdoor temperatures and intensive station usage). For each of the four locations, the electricity provision process was modelled based on the specific electricity generation fuel mix of the region. For Tel-Aviv, the unit process was constructed by adjusting the average German electricity generation process according to the local specific energy generation mix (IEA, 2016b). A similar approach was adopted to model the electric grid in Miami Beach, London, and Shanghai using the average Florida, UK, and China energy mixes respectably (DECC, 2016, EIA, 2016, IEA, 2016a). See Table SI-2 for a comparison of the average energy mixes of the four locations.

Total water consumption includes water delivered to consumers and the additional water required for container washing (0.01L/wash). To account for spillage or misuse by consumers, we add a general loss factor of 5% of total water usage. See Table 1 for an example of electricity and water consumption for three representative consumption scenarios.

To account for the high share of seawater desalination in Israel's municipal water mix (≈50%), the average European tap water process (RER) was adjusted to include the additional energy requirements of the Israeli system (3.5 kWh/m^3)(Tenne, 2010). Other locations are modelled using the average EU tap water process.

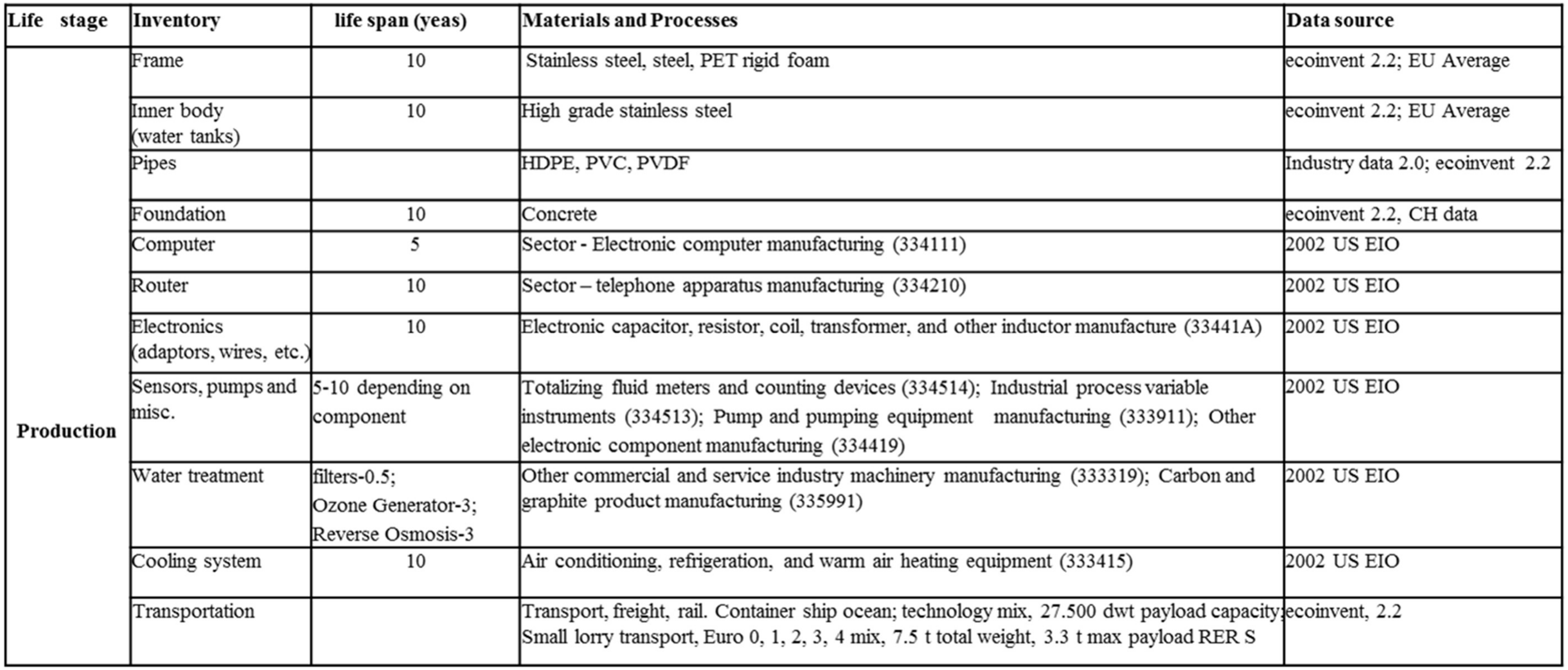
3.2.5 End of life management

Since recycling rates of electronic equipment are relatively low, EoL management of the Woosh station was conservatively assumed to be landfilling, and modelled on the basis of landfilling costs at each location (converted to 2002 US dollars) using EIO tables (see Table 3).

Table 1 : Example of electricity and water for different consumption scenarios

Total volume of drinking water consumed/day	**40L**	**75L**	**150L**
Total water consumed L/day (including bottle wash and loss)	43	80	161
Cooling			
total electricity consumed (kWh/day)	3.78	4.00	4.49
Electricity consumed per use (kWh/L)	0.094	0.053	0.030
No cooling			
total electricity consumed (kWh/day)	1.27	1.49	1.98
Electricity consumed per use (kWh/L)	0.032	0.020	0.013

Table 2: Woosh station life cycle inventory - Production



Life stage	Inventory	life span (yeas)	Materials and Processes	Data source
Production	Frame	10	Stainless steel, steel, PET rigid foam	ecoinvent 2.2; EU Average
	Inner body (water tanks)	10	High grade stainless steel	ecoinvent 2.2; EU Average
	Pipes		HDPE, PVC, PVDF	Industry data 2.0; ecoinvent 2.2
	Foundation	10	Concrete	ecoinvent 2.2, CH data
	Computer	5	Sector - Electronic computer manufacturing (334111)	2002 US EIO
	Router	10	Sector – telephone apparatus manufacturing (334210)	2002 US EIO
	Electronics (adaptors, wires, etc.)	10	Electronic capacitor, resistor, coil, transformer, and other inductor manufacture (33441A)	2002 US EIO
	Sensors, pumps and misc.	5-10 depending on component	Totalizing fluid meters and counting devices (334514); Industrial process variable instruments (334513); Pump and pumping equipment manufacturing (333911); Other electronic component manufacturing (334419)	2002 US EIO
	Water treatment	filters-0.5; Ozone Generator-3; Reverse Osmosis-3	Other commercial and service industry machinery manufacturing (333319); Carbon and graphite product manufacturing (335991)	2002 US EIO
	Cooling system	10	Air conditioning, refrigeration, and warm air heating equipment (333415)	2002 US EIO
	Transportation		Transport, freight, rail. Container ship ocean; technology mix, 27.500 dwt payload capacity; Small lorry transport, Euro 0, 1, 2, 3, 4 mix, 7.5 t total weight, 3.3 t max payload RER S	ecoinvent, 2.2

Table 3 : Woosh station life cycle inventory – Use and End of Life by location

Life stage	Inventory	Materials and Processes	Data source
Tel-Aviv Israel			
Use	Water	Tap water, at user + an additional 3.5 Kwh/cubic meter to account for desalination energy requirements typical for Israel	ecoinvent, 2.2; EU average
	Maintenance	transport of technition to site- scooter, assuming 50km total per bi-weekly visit to station	ecoinvent 2.2 , CH data
	Electricity	Electricity, low voltage, at grid, DE process adjusteded to represent average electricity generation mix in Israel in 2013	ecoinvent 2.2 ; DE average
	Part replacement	Sector - Electronic computer manufacturing (334111); Pump and pumping equipment manufacturing; Carbon and graphite product manufacturing (335991) ; Transport, freight, rail,	2002US EIO
	parts transport	Container ship ocean; technology mix, 27.500 dwt pay load capacity; Small lorry transport, Euro 0, 1, 2, 3, 4 mix, 7,5 t total weight, 3,3 t max payload RER S; distance calculated from production origin to the center of Tel-Aviv using a combination of transport modes	ecoinvent, 2.2 EU average
EoL	End of life	Sector - waste management and remediation services (562XX), at 100 Shekels/tonne	2002US EIO
Miami beach FL			
Use	Water	Tap water, at user	ecoinvent, 2.2; EU average
	Maintenance	transport of technition to site- scooter, assuming 50km total per bi-weekly visit to station	ecoinvent 2.2 , CH data
	Electricity	Electricity, low voltage, at grid, US process adjusted to represent average electricity generation mix for Florida in 2014	ecoinvent 2.2 ;U.S avreage
	Part replacement	Sector - Electronic computer manufacturing (334111); Pump and pumping equipment manufacturing; Carbon and graphite product manufacturing (335991) ; Transport, freight, rail,	2002US EIO
	parts transport	Container ship ocean; technology mix, 27.500 dwt pay load capacity; Small lorry transport, Euro 0, 1, 2, 3, 4 mix, 7,5 t total weight, 3,3 t max payload RER S; distance calculated from production origin to the center of Miami-Beach using a combination of transport modes	ecoinvent, 2.2; EU average
EoL	End of life	Sector - waste management and remediation services (562XX), at $50/tonne	2002US EIO
London, UK			
Use	Water	Tap water, at user	ecoinvent, 2.2; EU average
	Maintenance	transport of technition to site- scooter, assuming 50km total per bi-weekly visit to station	ecoinvent 2.2; CH data
	Electricity	Electricity, low voltage, at grid, GB process adjusted to represent average electricity generation mix for the UK in 2015	ecoinvent 2.2 ; GB avrage
	Part replacement	Sector - Electronic computer manufacturing (334111); Pump and pumping equipment manufacturing; Carbon and graphite product manufacturing (335991) ; Transport, freight, rail,	2002US EIO
	parts transport	Container ship ocean; technology mix, 27.500 dwt pay load capacity; Small lorry transport, Euro 0, 1, 2, 3, 4 mix, 7,5 t total weight, 3,3 t max payload RER S; distance calculated from production origin to the center of London using a combination of transport modes	ecoinvent, 2.2; EU average
EoL	End of life	Sector - waste management and remediation services (562XX), at 76 pounds/tonne,	2002US EIO
Shanghi, china			
Use	Water	Tap water, at user	ecoinvent, 2.2; EU average
	Maintenance	transport of technition to site- scooter, assuming 50km total per bi-weekly visit to station	ecoinvent 2.2 , CH data
	Electricity	Electricity, low voltage, at grid, CN process adjusted to represent average electricity generation mix in shanghi 2014	ecoinvent 2.2 ;CN avrage
	Part replacement	Sector - Electronic computer manufacturing (334111); Pump and pumping equipment manufacturing; Carbon and graphite product manufacturing (335991) ; Transport, freight, rail,	2002US EIO
	parts transport	Container ship ocean; technology mix, 27.500 dwt pay load capacity; Small lorry transport, Euro 0, 1, 2, 3, 4 mix, 7,5 t total weight, 3,3 t max payload RER S;distance calculated from production origin to the center of Shanghai using a combination of transport modes	ecoinvent, 2.2; EU average
EoL	End of life	Sector - waste management and remediation services (562XX), at $10/tonne	2002US EIO

3.3 Life cycle impact assessment

The environmental impact categories used in our analysis are Cumulative Energy Demand (CED) and global warming impact (GW) over 100 years using the IPCC 2007 framework. Previous work has shown that results for CED are highly correlated with those of several other major impact categories and reflect the relative contribution different processes or components make to the overall impacts assessed (Ashby, 2012, Huijbregts et al. , 2006). Therefore, CED was chosen as a proxy indicator for environmental impact. Using global warming impact indicator was chosen to enable comparison with previously-published work on bottled water that commonly report results in greenhouse gas equivalent units. However, to make our work more comparable with future studies, we also provide results for a range of additional impact categories in the supplementary information (see Table SI-1).

4 RESULTS

4.1 Environmental impacts of the Woosh station

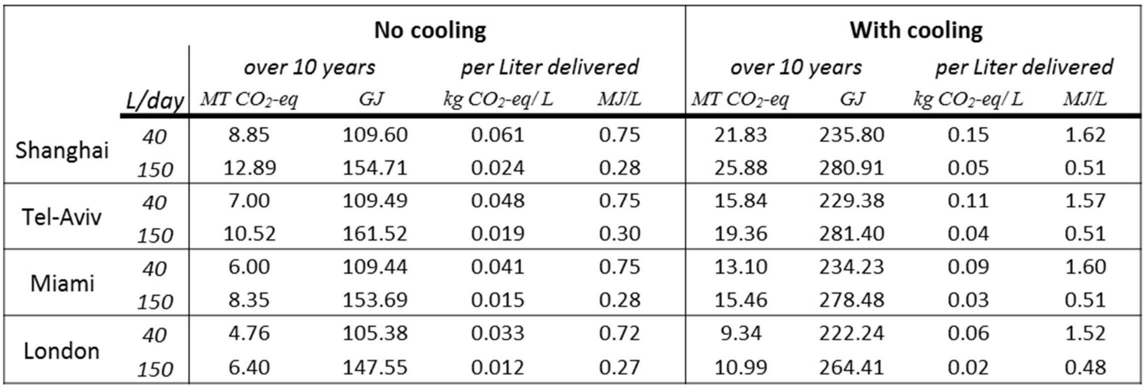
Our analysis shows that over a 10-year period overall CED and GW range from 105.4 – 281.4 GJ and 4.8–25.9 tonnes CO_2-eq, respectively, reflecting the maximal range provided by the 40 L/d no-cooling scenario and a 150 L/d with cooling scenario and the different locations modeled. On a per liter basis, CED and GW ranged between 0.27 MJ/L -1.62 MJ/L and 0.012 kg CO_2-eq/L - 0.15 kg CO_2-eq/L, with the magnitude depending on the consumption and cooling scenario (for 150 L/day no-cooling and 40 L/day with cooling respectively), and the electricity generation mix, (see Table for a summary of results by consumption scenario and location).

As Figure 2 depicts, the station's per-liter resource use and climate change impacts decreases as daily consumption volume increases. Since the actual filling and cleansing operations require an incremental addition to the baseline inputs (i.e. production, maintenance and standby mode electricity) dividing overall burdens by higher daily consumption volumes (to obtain results on a per liter basis) results in an exponentially-declining curve.

Figures 2a and 2b depict the relative contribution of the various factors (including production, routine maintenance, use-phase electricity etc.) to the overall CED in Tel-Aviv. For all consumption scenarios, use-phase electricity is the most prominent contributor for both the cooling (Figure 2a) and non-cooling (Figure 2b) options associated with over 50% of overall energy demand. These results suggest that the added burden of erecting new infrastructure is negligible compared to the requirements incurred during the use phase, and specifically electricity consumption. As expected, serving water at room temperature is more energy efficient than delivering chilled water, explaining the differences between the curves in Figures 2a and 2b.

Figures 2c and 2d portray the potential GW impacts per consumption scenario in the different locations modeled. Similar to the CED results, higher consumption rates and no-cooling result in lower GW impacts compared to low consumption and cooling scenarios. In addition, the station's overall GW performance varies, and could be almost two times worse when connected to a carbon-intensive grid such as the one in Shanghai compared to a 'cleaner' grid such as the one in London. These results demonstrate that the environmental impact associated with the water station in highly sensitive to a country's electricity production fuel mix.

Table 4. Overall and per liter results for high and low consumption scenarios by location



		No cooling				With cooling			
		over 10 years		per Liter delivered		over 10 years		per Liter delivered	
	L/day	MT CO_2-eq	GJ	kg CO_2-eq/ L	MJ/L	MT CO_2-eq	GJ	kg CO_2-eq/ L	MJ/L
Shanghai	40	8.85	109.60	0.061	0.75	21.83	235.80	0.15	1.62
	150	12.89	154.71	0.024	0.28	25.88	280.91	0.05	0.51
Tel-Aviv	40	7.00	109.49	0.048	0.75	15.84	229.38	0.11	1.57
	150	10.52	161.52	0.019	0.30	19.36	281.40	0.04	0.51
Miami	40	6.00	109.44	0.041	0.75	13.10	234.23	0.09	1.60
	150	8.35	153.69	0.015	0.28	15.46	278.48	0.03	0.51
London	40	4.76	105.38	0.033	0.72	9.34	222.24	0.06	1.52
	150	6.40	147.55	0.012	0.27	10.99	264.41	0.02	0.48

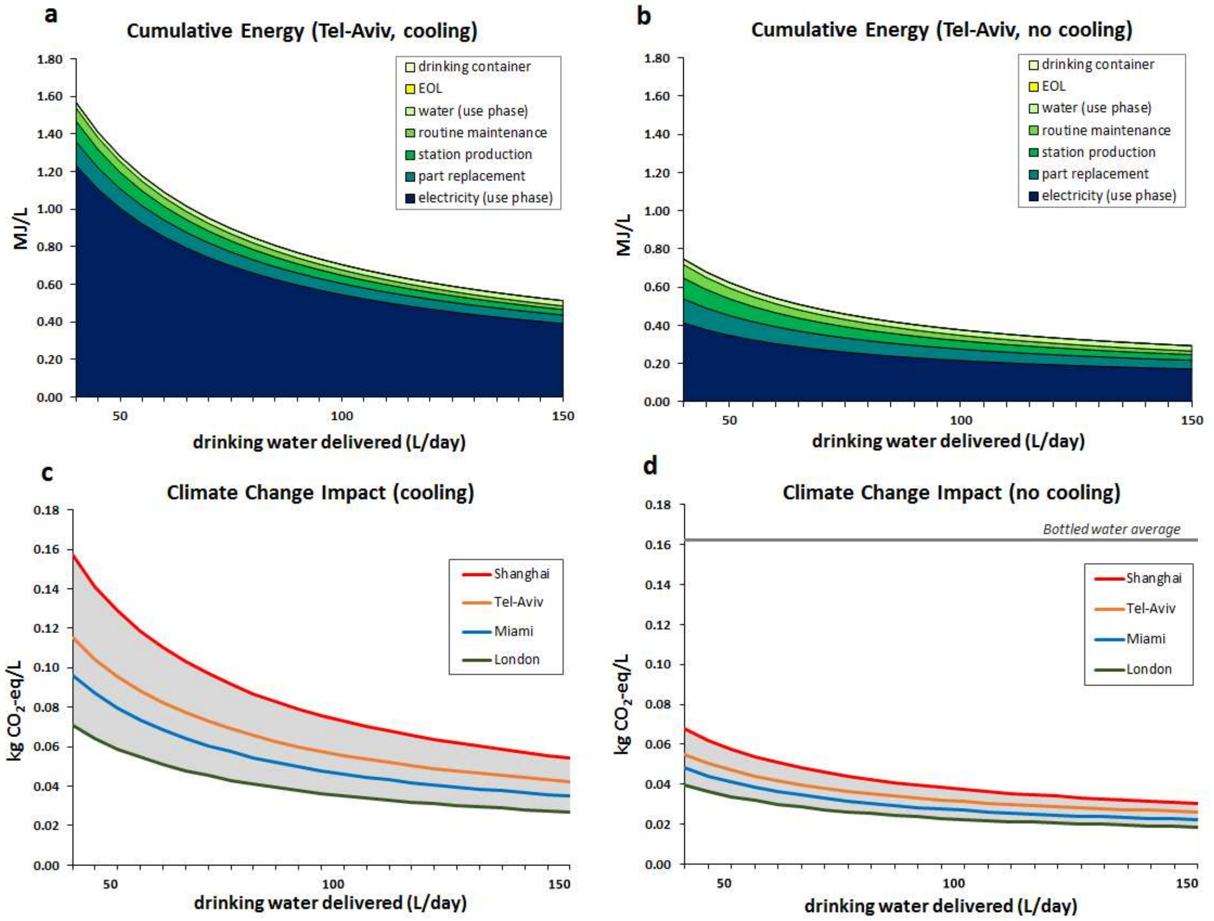


Figure 2. Woosh station per liter CED and GHG emissions as a function of water volume consumed daily for cooled (panels a,c) and room temperature (panels b,d) scenarios. In the CED cases (panels a,b) the colored layers represent each component's contribution to overall energy demand in ascending order. In the GHG cases (panels c,d) the gray area represents GHG emissions range when connecting to various electricity grids with different GHG efficiency levels – Israeli grid (orange), Chinese grid (red), average US grid (blue) and average EU grid (green). Bottled water's average GHG emissions per L are shown in gray (harmonized value for non-cooled bottles transported 100 km) in panel d.

4.2 Sensitivity analysis

A sensitivity analysis was performed on parameters that were expected to significantly impact results. As mentioned previously use-phase electricity was responsible for over 50% of CED and CC impacts in all locations. Since transport of parts was not substantial, the variance in results between the four locations is driven by the difference in electricity generation fuel mix. This suggests that results are highly sensitive to electricity production and provision.

Another concern was that the additional energy demand of a network of water stations may influence peak electricity demand, thus changing the electricity generation landscape. Therefore, we examined what impact, if any, a high degree of water station use could have on total energy demand in Israel. We found that if the daily amount of water consumed from the water station network was equal to the amount of daily bottled water consumption (827,500 L), and all water was delivered cooled and within the hour of peak electricity demand in Israel, the required electricity would be about 113MWh, or less than 1% of daily peak demand of 11,530MW (Ministry of National Infrastructure Energy & Water Resources, 2015).

To examine whether the unique water mix in Israel has a substantial bearing on the results, we conducted a sensitivity analysis by substituting Israel's desalination-adjusted water mix with the average Swiss tap water provision process. when examining water-quality impact categories (water depletion, freshwater ecotoxicity, and freshwater eutrophication), we found no substantial difference in the results between the two models. For energy however, the additional energy required for the production a of liter of desalinated water, accounted for x-y% of over all CC related impact and xx MJ. requirements of desalination ranged between 4%-30%

4.3 Woosh stations vs. bottled water

Although water delivery stations such as Woosh are commonly seen as ‘greener’ than bottled water, only a few studies have compared the two delivery systems ‘head to head’. Thus, in this section we begin by assessing the average climate change impact associated with bottled water based on a review of LCAs published in academic and professional literature. We then proceed to compare our LCA results for the Woosh station to those of an ‘average’ bottle of water.

Reported greenhouse gas emission factors from bottled water range from 0.1 kg CO_2-eq/L to 0.5 kg CO_2-eq/L, but the disparity can be partially attributed to non-uniformity in analytical approach. Variable functional units, system boundaries, assumption regarding transport distance, and other parameters, with the higher values representing scenarios that include refrigeration, high energy-intensive treatment, and/or long distance transport all likely influenced the range of reported emission values (Botto, 2009, Dettling, Tatti, 2010, Dettore, 2009, Fantin, Scalbi, 2014, Franklin Associates, 2009, Jungbluth, 2006, Nessi, Rigamonti, 2012, Nestlé Waters, 2010). In light of the variable results for bottled water in the literature, we compare our results for the water station to an ‘average bottled water system’, presented by Fantin, Scalbi (2014).

In their paper Fantin, Scalbi (2014) report a generic method for performing a meta-analysis of LCA studies through a harmonization of various system boundaries (see

Figure 1b) and key assumptions. Their generic methodology is based on an iterative six steps approach, which main steps include choosing appropriate studies, identifying leading parameters (system boundaries, functional units, assumptions, allocations, etc.) and harmonizing them into a uniform set. In the case of bottled water, for example, differences in functional unit and transportation distances can explain a large share of the variance in results. Therefore, to derive an average result, they adjust the different models to represent a uniform functional unit of 1L of water, a transport distance of 100 km between producer and retailer (in a truck with average load), and a non-cooled scenario. The results of the harmonized average is 0.16 kg CO_2-eq ± 0.009 kg CO_2-eq (see Figure 2c).

In comparison to our LCA results, this value is approximately two to six times greater than the potential GW of 1L delivered from the water station for the highest impact found (40L/day in Shanghai) and lowest impact found (150L/day in London), respectively.

5 DISCUSSION

The life-cycle impacts of the Woosh station are governed mostly by its use-phase inputs. Specifically, the electricity consumed during operation accounts for the vast majority of overall CED and GW impacts. Across multiple scenarios and locations, the results demonstrate that the consumption of water from the Woosh station has lower GW impacts than bottled water (when served at room temperature). Thus, the potential benefits from the water stations depend on how much bottled water will be replaced in practice. In terms of cost, purchasing water from the stations is expected to be less expensive than bottled water in many cases, but more expensive than municipally-provided water. Although location-specific variables will impact system-wide costs (e.g., utility hook-ups, design, permitting, installation, and ongoing maintenance), a recent example in Miami Beach shows a cost to consumer for a 0.6-L refill of chilled, filtered water is approximately 70% less than an average-priced bottle of water (City of Miami Beach., 2016).

The substitution rates between bottle refills and the purchase of bottled water may be difficult to assess in light of many influencing factors (e.g., cost, consumer preference, potential rebound effects, etc.). However, a simple calculation is useful to understand the scale of potential impacts. In 2010, 302 million liters of bottled water were sold in Israel. Substituting only 10% of these sales by water from Woosh stations would result in a reduction of approximately 3,850-4,500 tonnes of CO_2-eq annually (for average consumption of 40 L/day and 150 L/day at room temperature respectively). This reduction would be equivalent to taking approximately 2,000-2,700 cars off of the road each year (assuming 130 gCO_2-eq/km and 15,000 km/year).

Substituting bottled water for water delivered from water stations could also reduce the amount of plastic waste. Although PET is one of the most valuable and commonly recycled polymers, collection rates in many developed countries remain relatively low. For example, estimates suggests that in the US less than 40% of single-serve PET water bottles were recycled in 2014 (IBWA, 2016). Yet even if an unrealistic goal of 100% recycling rate was achieved globally, the recycling process would still require additional energy and material inputs, and will likely incur leakage of materials and material downgrade. In addition, substituting single-serve water bottles with filtered water from refill stations would not only eliminate waste at its source, it would also ripple through the supply chain, reducing environmental pressures related to transportation, storage and end of life treatment.

Ultimately, from a policy perspective it would seem that even at a low consumption level of and low substitution rates encouraging the use of water stations represents an opportunity to reduce overall environmental impacts at the municipal level. However, another possibility is that water from a Woosh station will not replace bottled water but will be consumed in addition, reflecting an overall increase in the absolute amount of water consumed in the public sphere. Although such a trend would also increase the total environmental impact associated with consumption of water on-the-go (especially if the water is served chilled and consumption rises in locations with a carbon intense grid such as Shanghai), it would most likely hold public health benefits resulting from higher water intake (Jéquier and Constant, 2010, Mann, 2013), at a relatively low environmental cost.

The public health and well-being benefits of such water delivery systems are also relevant in many developing countries that lack centralized water systems (Sima and Elimelech, 2013), or in places where such infrastructure is compromised due to disasters or contamination issues (e.g. following the recent events in Flint Michigan, USA). Decentralized water treatment and refill stations such as the one analyzed here, could potentially fill the need for safe drinking water while reducing reliance on packaged water. Future work is needed to assess the potential benefits filtered water delivery stations may have in locations that require additional supporting infrastructure (e.g. decentralized energy provision).

6 CONCLUSIONS AND LIMITATIONS

Water refill stations that provide consumers access to filtered water even when they are on-the-go. In this study we find that the climate change impacts associated with water delivered from a water station are less than those of an average bottled water system under a wide range of consumption and electricity generation scenarios. Clearly, the greatest potential for environmental benefits occurs in regions that have less carbon-intensive electricity grids. Environmental gains could potentially be further realized when coupling water stations with renewable decentralized electricity systems (e.g., solar or wind).

Consumption rate (e.g. how many liters does that station provide daily) is also a major factor dictating the environmental impacts per liter of water delivered, with lower relative impacts observed in high-demand scenarios. Thus, optimal siting of water stations will be in areas with high amounts of pedestrian traffic. Ultimately, overall environmental benefits will be realized only with behavior change whereby bottled water consumption is reduced and drinking water station consumption increases.

The results presented here have some important limitations. First, because LCA inventory data for China and Israel are scarce, we used average European values for most product-based LCA materials, and, 2002 US$ values for the EIO-LCA components. A more region-specific production processes and a regional EIO table could have improved accuracy. Second, estimates for use-phase electricity demand for the Woosh station were based on controlled laboratory experiments, thus actual electricity use during full-scale use may differ. Finally, long-term performance data of the stations are not available, which represents a source of potential uncertainty. The variability in consumption and use scenarios, though, should dampen the overall influence of these limitations on the results.

ACKNOWLEDGMENTS

This material is based in part upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-1122492. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the NSF or the U.S. Government.

6. REFERENCES

Ashby MF. Materials and the environment: eco-informed material choice: Elsevier; 2012.

Barrios R, Siebel M, van der Helm A, Bosklopper K, Gijzen H. Environmental and financial life cycle impact assessment of drinking water production at Waternet. Journal of Cleaner Production. 2008;16:471-6.

Beckman DS. The Threats to Our Drinking Water. The New York Times: New York Times
2014.

Beverage Marketing Corporation. Bottled Water Sustains Strength. 2014.

Bilec M, Ries R, Matthews H, Sharrard A. Example of a Hybrid Life-Cycle Assessment of Construction Processes. Journal of Infrastructure Systems. 2006;12:207-15.

Botto S. Tap water vs. bottled water in a footprint approach. 2009.

Botto S, Niccolucci V, Rugani B, Nicolardi V, Bastianoni S, Gaggi C. Towards lower carbon footprint patterns of consumption: The case of drinking water in Italy. Environmental Science & Policy. 2011;14:388-95.

City of Miami Beach. Execute agreement: Citywide network of smart drinking water stations. city of Miami Beach offcial website: city of Miami Beach; 2016.

Daniels MC, Popkin BM. Impact of water intake on energy intake and weight status: a systematic review. Nutrition Reviews. 2010;68:505-21.

DECC. UK Energy Statistics, 2015 & Q4 2015. In: Change DoEaC, editor.2016.

Dettling J, Tatti E, Ace J. Environmental life cycle assessment of drinking water alternatives and consumer beverage consumption in North America. North America Project Report2010.

Dettore CG. Comparative life-cycle assessment of bottled vs. tap water systems. Ann Arbor. 2009.

EIA. Table 5. Electric power industry generation by primary energy source, 1990 through 2014 2016 ed: U.S. Energy Information Administration; 2016.

Fantin V, Scalbi S, Ottaviano G, Masoni P. A method for improving reliability and relevance of LCA reviews: The case of life-cycle greenhouse gas emissions of tap and bottled water. Science of The Total Environment. 2014;476–477:228-41.

Franklin Associates. Life cycle assessment of drinking water system: bottle water, tap water, and home/office delivery water. evised Final peer-reviewed LCA report, 2009. 09-LQ-104 22 october 2009. 2009.

Friedrich E. Life-cycle assessment as an environmental management tool in the production of potable water. Water Science & Technology. 2002;46:29-36.

Friedrich E, Pillay S, Buckley C. Carbon footprint analysis for increasing water supply and sanitation in South Africa: a case study. Journal of Cleaner Production. 2009a;17:1-12.

Friedrich E, Pillay S, Buckley C. Environmental life cycle assessments for water treatment processes a South African case study of an urban water cycle. Water SA. 2009b;35:73-84.

Ganim S, Tran L. How tap water became toxic in Flint, Michigan. CNN.com; 2016.

Grady C, Younos T. Bottled water technology and its global ramifications: An overview. Int Water Technol J. 2012;2:185-94.

Hendrickson C, Horvath A, Joshi S, Lave L. Peer reviewed: economic input–output models for environmental life-cycle assessment. Environmental science & technology. 1998;32:184A-91A.

Hu Z, Morton LW, Mahler RL. Bottled water: United States consumers and their perceptions of water quality. International journal of environmental research and public health. 2011;8:565-78.

Huijbregts MA, Rombouts LJ, Hellweg S, Frischknecht R, Hendriks AJ, van de Meent D, et al. Is cumulative fossil energy demand a useful indicator for the environmental performance of products? Environmental Science & Technology. 2006;40:641-8.

IBWA. PET facts. 2016.

IEA. China: Electricity and heat for 2013. International Energy Agency; 2016a.

IEA. Israel: Electricity and heat for 2013. International Energy Agency; 2016b.

Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady A, et al. Plastic waste inputs from land into the ocean. Science. 2015;347:768-71.

Jéquier E, Constant F. Water as an essential nutrient: the physiological basis of hydration. European journal of clinical nutrition. 2010;64:115-23.

Joshi S. Product environmental life ‐ cycle assessment using input ‐ output techniques. Journal of Industrial Ecology. 1999;3:95-120.

Jungbluth N. Comparison of the environmental impact of drinking water vs. bottled mineral water. Manuscript for the SGWA information bulletin and gwa (Gas Water Sewage) Disponible sur: www trinkwasser ch. 2006.

Mann L. Study finds nearly half of Americans not drinking enough water. Chicago Tribune. Chicago Tribune website2013.

Matthews HS, Small MJ. Extending the boundaries of life-cycle assessment through environmental economic input-output models. Journal of Industrial Ecology. 2000;4:7-10.

Ministry of National Infrastructure Energy & Water Resources. Israel2015.

Murray A, Horvath A, Nelson KL. Hybrid life-cycle environmental and cost inventory of sewage sludge treatment and end-use scenarios: a case study from China. Environmental science & technology. 2008;42:3163-9.

Nessi S, Rigamonti L, Grosso M. LCA of waste prevention activities: A case study for drinking water in Italy. Journal of Environmental Management. 2012;108:73-83.

Nestlé Waters. Nestlé Waters – Creating shared value report 2005-2010. 2010.

Nick S. Italy bans the plastic water bottle along heritage coastline. The Telegraph. UK2010.

Parker L, Burns AC, Sanchez E. Local government actions to prevent childhood obesity: National Academies Press; 2009.

Polizzi di Sorrentino E, Woelbert E, Sala S. Consumers and their behavior: state of the art in behavioral science supporting use phase modeling in LCA and ecodesign. The International Journal of Life Cycle Assessment. 2016;21:237-51.

Sima LC, Elimelech M. More than a Drop in the Bucket: Decentralized Membrane-Based Drinking Water Refill Stations in Southeast Asia. Environmental Science & Technology. 2013;47:7580-8.

Tarantini M, Ferri F. A life cycle assessment study of the environmental sustainability of domestic water saving techniques. Sustainable Plann Dev. 2003;6:579-89.

Tenne A. Sea Water Desalination in Israel: Planning, coping with difficulties, and economic aspects of long-term risks. 2010.

Torretta V. Environmental and economic aspects of water kiosks: Case study of a medium-sized Italian town. Waste management. 2013;33:1057-63.

Unicef, Organization WH. Progress on sanitation and drinking water: 2014 update: World Health Organization; 2014.

Vince F, Aoustin E, Bréant P, Marechal F. LCA tool for the environmental evaluation of potable water production. Desalination. 2008;220:37-56.

Wendy K. Battle brews over bottled water. USA Today2010.

SUPPLEMENTARY INFORMATION

Table SI-1. ReCiPe Midpoint (H) V1.06 / Europe results for a Woosh water station located in Tel-Aviv Israel under highest impact scenario (150 L/day, cooling, IL electricity grid)

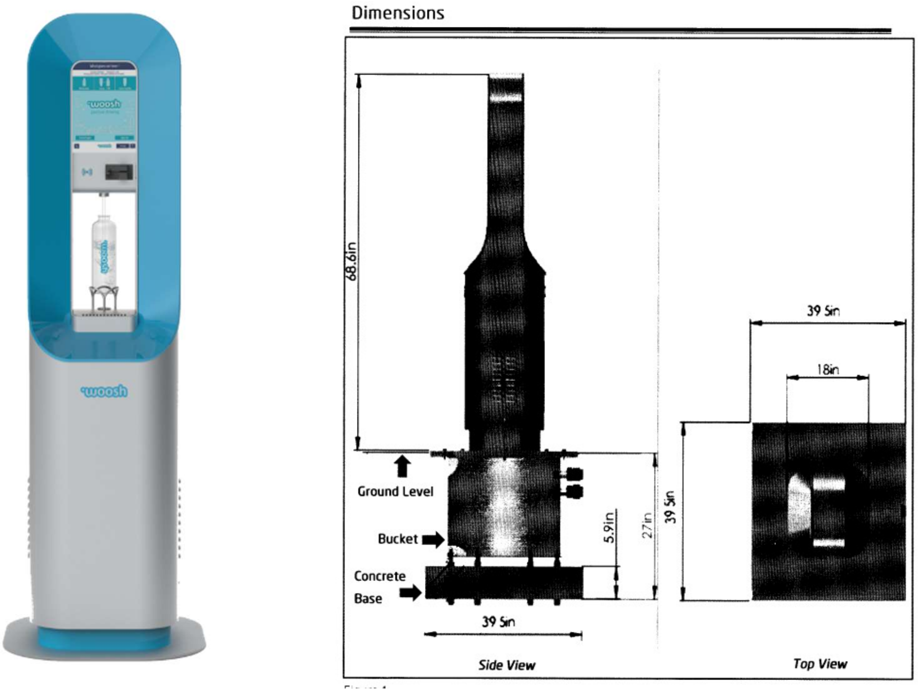
Impact category	**Unit**	**Total**	**Production**	**Part Replacement**	**Routine Maintenance**	**Water (use phase)**	**Electricity (use phase)**	**EOL**
Climate change	kg CO2 eq	1.95E+04	9.32E+02	9.09E+02	7.03E+02	1.09E+03	1.58E+04	4.59E+01
			5%	*5%*	*4%*	*6%*	*81%*	*0%*
Ozone depletion	kg CFC-11 eq	6.63E-03	2.04E-03	3.60E-03	9.20E-05	5.66E-05	8.27E-04	1.08E-05
			31%	*54%*	*1%*	*1%*	*12%*	*0%*
Human toxicity	kg 1,4-DB eq	3.78E+03	1.17E+02	4.44E+01	6.96E+01	2.63E+02	3.28E+03	3.79E+00
			3%	*1%*	*2%*	*7%*	*87%*	*0%*
Photochemical oxidant formation	kg NMVOC	4.49E+01	1.91E+00	1.13E+00	2.12E+01	1.56E+00	1.91E+01	1.04E-02
			4%	*3%*	*47%*	*3%*	*42%*	*0%*
Particulate matter formation	kg PM10 eq	1.43E+01	2.21E+00	3.04E+00	8.71E-01	6.79E-01	7.42E+00	3.05E-02
			15%	*21%*	*6%*	*5%*	*52%*	*0%*
Lonising radiation	kg U235 eq	3.92E+02	4.52E+01	5.50E+00	2.85E+01	1.25E+02	1.88E+02	x
			12%	*1%*	*7%*	*32%*	*48%*	
Terrestrial acidification	kg SO2 eq	3.08E+01	1.79E+00	1.86E+00	2.09E+00	1.98E+00	2.31E+01	7.47E-03
			6%	*6%*	*7%*	*6%*	*75%*	*0%*
Freshwater eutrophication	kg P eq	4.00E+00	7.72E-02	9.25E-03	4.83E-02	3.21E-01	3.55E+00	5.65E-05
			2%	*0%*	*1%*	*8%*	*89%*	*0%*
Marine eutrophication	kg N eq	1.80E+00	1.09E-01	6.57E-02	8.91E-02	1.24E-01	1.41E+00	4.62E-04
			6%	*4%*	*5%*	*7%*	*78%*	*0%*
Terrestrial ecotoxicity	kg 1,4-DB eq	9.71E-01	1.03E-01	1.12E-01	1.14E-01	5.26E-02	5.41E-01	5.02E-02
			11%	*11%*	*12%*	*5%*	*56%*	*5%*
Freshwater ecotoxicity	kg 1,4-DB eq	7.31E+01	6.21E+00	4.34E-01	1.54E+00	6.40E+00	5.85E+01	1.74E-02
			8%	*1%*	*2%*	*9%*	*80%*	*0%*
Marine ecotoxicity	kg 1,4-DB eq	7.54E+01	6.37E+00	4.04E-01	2.04E+00	5.50E+00	6.10E+01	1.21E-02
			8%	*1%*	*3%*	*7%*	*81%*	*0%*
Agricultural land occupation	m2a	3.31E+02	3.77E+00	1.83E-01	2.35E+00	2.89E+01	2.96E+02	5.24E-08
			1%	*0%*	*1%*	*9%*	*89%*	*0%*
Urban land occupation	m2a	8.56E+01	2.49E+00	3.10E-01	1.58E+00	1.25E+01	6.87E+01	x
			3%	*0%*	*2%*	*15%*	*80%*	
Natural land transformation	m2	2.27E+00	3.16E-02	2.70E-03	2.46E-01	1.65E-01	1.82E+00	x
			1%	*0%*	*11%*	*7%*	*80%*	
Water depletion	m3	7.11E+02	2.88E+00	9.29E-02	1.25E+00	6.63E+02	4.37E+01	x
			0%	*0%*	*0%*	*93%*	*6%*	
Metal depletion	kg Fe eq	7.49E+02	2.69E+02	3.62E+01	2.20E+01	1.63E+01	4.05E+02	1.01E-01
			36%	*5%*	*3%*	*2%*	*54%*	*0%*
Fossil depletion	kg oil eq	6.21E+03	2.63E+02	3.43E+02	2.35E+02	3.36E+02	5.03E+03	2.39E+00
			4%	*6%*	*4%*	*5%*	*81%*	*0%*

Table SI-2. Electricity production grid mix by percent for Tel-Aviv, Israel (2013); Miami Beach, Florida (2014); London, UK (2015); and Shanghai, China (2011)

Generation Source	Tel-Aviv	Miami Beach	London	Shanghai
Coal	53.5	22.6	22.6	75.5
Hydroelectric	-	0.1	1.9	16.9
Natural Gas	41.9	60.9	29.6	1.7
Nuclear	-	12.1	20.8	2.1
Other Biomass	-	1.0	-	0.2
Other Gas	-	-	-	-
Petroleum	3.6	0.8	-	0.1
Solar	0.8	0.1	2.3	0.3
Wood	-	1.1	-	-
Other	0.2	1.3	20.6	

Notes: 1. Totals may not sum to 100 due to rounding. 2. A “-“ indicates contribution <0.1%.

Figure SI-1 – the Woosh station



Source: https://www.wooshwater.com/about.aspx\