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Better than bottled water?—Energy and climate change impacts of on-the-go drinking water stations

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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 cumulative 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.

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) bottled water (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 world health Organization, 2014), in the developed world, people usually have the luxury to choose 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 (where high concentrations of lead were found in tap water) 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 (Lagioia et al., 2012), 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

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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, 2009b; Jungbluth, 2006; Nessi et al., 2012; Parker et al., 2009; Tarantini and Ferri, 2003; Vince et al., 2008) with only few studies focusing on other public-sphere water supply alternatives such as water fountains or refill stations (Nessi et al., 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 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 4.3). 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 station

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 from 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 to \$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 hybrid-LCA to evaluate the environmental performance of water delivery from a water filtration station located in a public area. The energy demand and climate change 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 various 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 L 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 patterns. The wide range and incremental nature of the scenarios modeled helps reveal the conditions under which eco-efficiency is optimized.

3.1.1. Functional unit and system boundaries

We define the functional unit as 1 L 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 Fig. 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. Since reusable drinking containers are available on the market in various sizes and materials of construction, adopting results from Franklin Associates (2009) we chose a relatively high impact drinking container for our model – a 600 mL aluminum container. In addition to energy and CC impacts related to production, transport and EoL (as reported by Franklin Associates (2009)), we also include the water and energy required for washing the reusable container at the water station prior to each refill. 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.

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 were 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 (Meylan et al., 2014). The modelling approach is functional, as we choose to use a process- or EIO-based approach depending on data availability. However, relying on EIO data thus exposes us to possible aggregation errors (Lenzen, 2000; Majeau-Bettez et al., 2011; Williams et al., 2009): we are modelling the environmental impacts of an economic sector instead of a specific good or service within that sector. However, as EIO based data was used mainly to model production, the resulting aggregation errors should remain relatively small since the relevant components do not account for a large share of the full life cycle inputs.

3.1.3. Life cycle inventory

We first describe the main data sources and databases used to set up the life cycle inventory for providing 1 L 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

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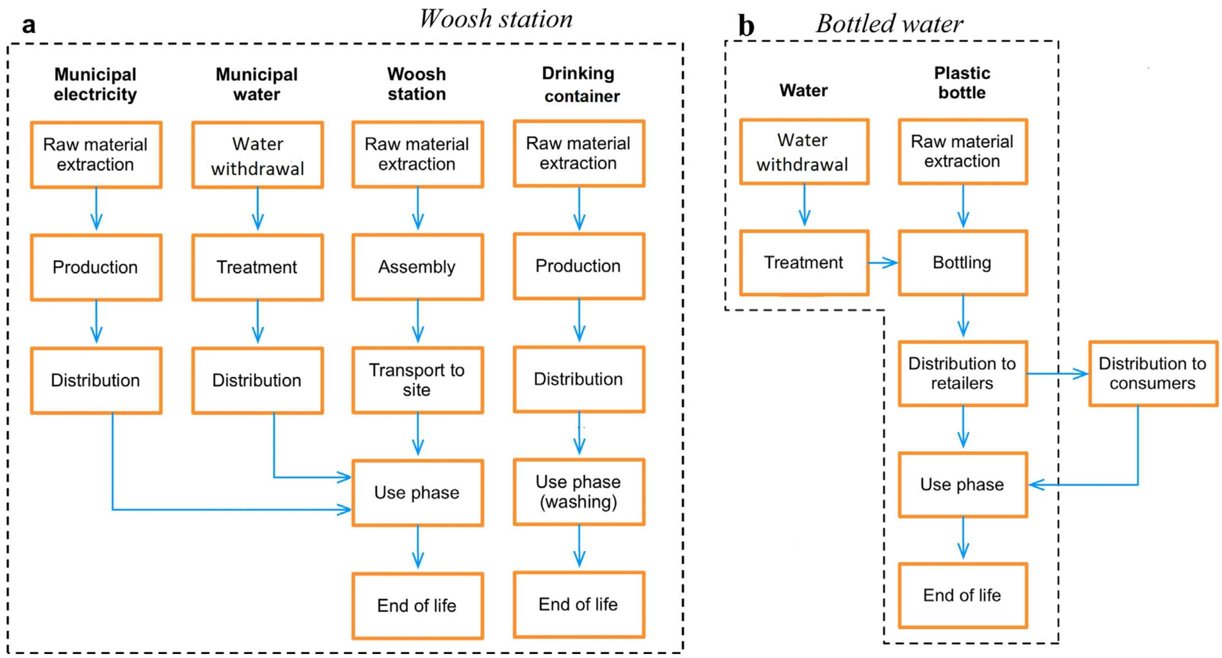

Fig. 1. System boundaries of the (a) Woosh station and (b) bottled water.

summarizes the data used to compile the inventoried life cycle processes for the Woosh station's production and Table 3 summarizes the data for the use and EoL phases at the various modelled locations.

3.1.4. 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).

3.1.5. 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 Fig. SI-1 for a photo of the Woosh station and dimensional specifications). Our model assumed that all long hall domestic transport (over 100 km) was done by rail, domestic short hall transport was done by lorry, and international transport by container ship to the closest industrial harbour.

3.1.6. 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.

3.1.7. Use-phase electricity and water

Use-phase electricity consumption was estimated based on data from a power consumption test conducted in September 2013 and calculated as follows. First, baseline 'stand- by' energy consumption and 'in-use' (i.e. filling and container rinsing) energy consumption were measured for non-cooling and cooling modes under extreme conditions (i.e. warm outdoor temperatures and consecutive filling and rinsing). Next, total 'in-use' electricity was compared to the stand-by mode to derive the net addition in energy required for filling 0.6 L of water (including cleansing and spillage). To derive total electricity use per filling we first extrapolated baseline energy demand to 24 h, and then added the daily net addition required for delivering the overall gross water volume in each scenario. For example, in the 40 L/day scenario, overall gross water withdrawal adds up to 43L when taking into account container washing and water loss (see Table 1). Finally, daily electricity consumption was divided by the net volume of water delivered to consumers (e.g. 40L, see Table 1) to derive values of electricity usage per litre for each scenario (see Table 1).

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,

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Table 2
Woosh station inventoried life cycle processes – Production.[a]

Life stage	Inventory	life span (years)	Materials and Processes	Data source
Production	frame	10	Stainless steel, steal, PET rigid foam	ecoinvent, 2.2; EU average
	Inner body (water tanks)	10	High grade stainless steal	ecoinvent, 2.2; EU average
	pipes	10	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)	2002US EIO
	router	10	Sector – telephone apparatus manufacturing (334210)	2002US EIO
	Electronics (e.g. adaptors, wires, etc.)	10	Electronic capacitor, resistor, coil, transformer, and other inductor manufacture (33441A)	2002US EIO
	Sensors, pumps and misc.	5–10 depending on spesific compnent	Totalizing fluid meters and counting devices (334514); Industrial process variable instruments (334513); Pump and pumping equipment manufacturing (333911); Other electronic component manufacturing (334419)	2002US 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)	2002US EIO
	Cooling system	10	Air conditioning, refrigeration, and warm air heating equipment (333415)	2002US EIO
	Transportation		Transport, freight, rail; 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	ecoinvent, 2.2

[a] Exact process quantities per functional unit are not reported due to business confidentiality issues.

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

Total volume of drinking water delivered/day	40 L	75 L	150 L
Total water withdrawal L/day (including bottle wash and loss)	43	80	161
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
Cooling			
Total electricity consumed (kWh/day)	3.78	4.00	4.49
Electricity consumed per use (kWh/L)	0.094	0.053	0.030

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 included water delivered to consumers and the additional water required for container washing (0.01 L/wash). It is assumed that drinking containers are washed using the station's built in washing function prior to each refill. 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.

Water use was modelled using the average European tap water process. 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).

3.1.8. *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).

3.2. *Life cycle impact assessment*

The environmental impact categories used in our analysis are Cumulative Energy Demand (CED) and climate change impact (CC) 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 have on the overall impacts assessed (Ashby, 2012; Huijbregts et al., 2006). Therefore, CED was chosen as a proxy indicator for environmental impact. The climate change 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).

3.3. *Woosh station 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, 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. The literature review revealed that reported greenhouse gas emission factors from bottled water range from

Table 3
Woosh station inventoried life cycle processes – 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 50 km 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 0–4 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/t	2002US EIO
Miami beach FL use			
	Water	Tap water, at user	ecoinvent, 2.2; EU average
	Maintenance	transport of technition to site- scooter, assuming 50 km 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;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 0–4 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/t	2002US EIO
London, UK use			
	Water	Tap water, at user	ecoinvent, 2.2; EU average
	Maintenance	transport of technition to site- scooter, assuming 50 km 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 0–4 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/t	2002US EIO
Shanghi, china use			
	Water	Tap water, at user	ecoinvent, 2.2; EU average
	Maintenance	transport of technition to site- scooter, assuming 50 km 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 0–4 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/t	2002US EIO

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 et al., 2010; Dettore, 2009; Fantinet al., 2014; Franklin Associates, 2009; Jungbluth, 2006; Nessi et al., 2012; Nestlé Waters, 2010).

In their paper Fantin et al. (2014) report a generic method for performing a meta-analysis of LCA studies through a harmonization of various system boundaries (see Fig. 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 1 L of water, a transport distance of 100 km between producer and retailer (in a truck with average load), and a non-cooled scenario. To minimize the modeling differences between the reviewed paper, and enable a more direct comparison of bottled water to the water station studied here, we compare our results for the water station to those of the 'average bottled water system' presented by Fantin et al. (2014).

4. Results

4.1. Environmental impacts of the Woosh station

Our analysis shows that over a 10-year period overall CED and CC range from 105.4–281.4 GJ and 4.8–25.9 t 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 CC 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 Fig. 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.

Fig. 2a and b 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 (Fig. 2a) and non-cooling (Fig. 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. In particular, the impacts from production, part replacement and end of life that were modelled exclusively using an EIO approach, are small compared to those of the use phase. Thus, possible aggregation errors arising from this modeling approach are likely to be small. As expected, serving water at room temperature is more energy efficient than delivering chilled water, explaining the differences between the curves in Fig. 2a and b.

Fig. 2c and d portray the potential CC impacts per consumption scenario in the different locations modeled. Similar to the CED results, higher consumption rates and no-cooling result in lower CC impacts compared to low consumption and cooling scenarios. In addition, the station's overall CC 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 (see Table 4). These results demonstrate that the environmental impact associated with the water station in highly sensitive to a country's electricity production fuel mix.

4.2. Comparison to bottled water

In light of the variable results for bottled water in the literature, we compare our results for the water station to those of the 'average bottled water system', presented by Fantin et al. (2014). They find that on average the CC impact associated with bottled water are 0.16 kg CO_2-eq ± 0.009 kg CO_2-eq (see Fig. 2c). In comparison to our LCA results, this value is approximately two to six times greater than the potential CC of 1 L delivered from the water station for the highest impact found (40 L/day in Shanghai) and lowest impact found (150 L/day in London), respectively.

4.3. Sensitivity analysis

To examine whether the unique water mix in Israel had a substantial bearing on the results for this location, we conducted a sensitivity analysis by substituting Israel's desalination-adjusted water mix with the average European tap water provision process (RER). In water-quality impact categories (water depletion, freshwater ecotoxicity, and freshwater eutrophication), the desalination-adjusted model resulted in an incremental increase of 3% compared to the average EU model (see Table 3 in the SI). In CC and CED, however, the desalination-adjusted model resulted in higher impacts compared with the average EU model suggesting that water production process should indeed be taken into account when considering the environmental performance of such water delivery systems.

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 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 (see Table 2 in the SI).

Nonetheless, across multiple scenarios and locations, the results demonstrate that the consumption of water from the Woosh station has lower CC 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 3850–4500 metric tons (t) 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 2000–2700 cars off of the road each year (assuming 130 g CO_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 2013–2014 (IBWA, 2016; Kang et al., 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 rip-

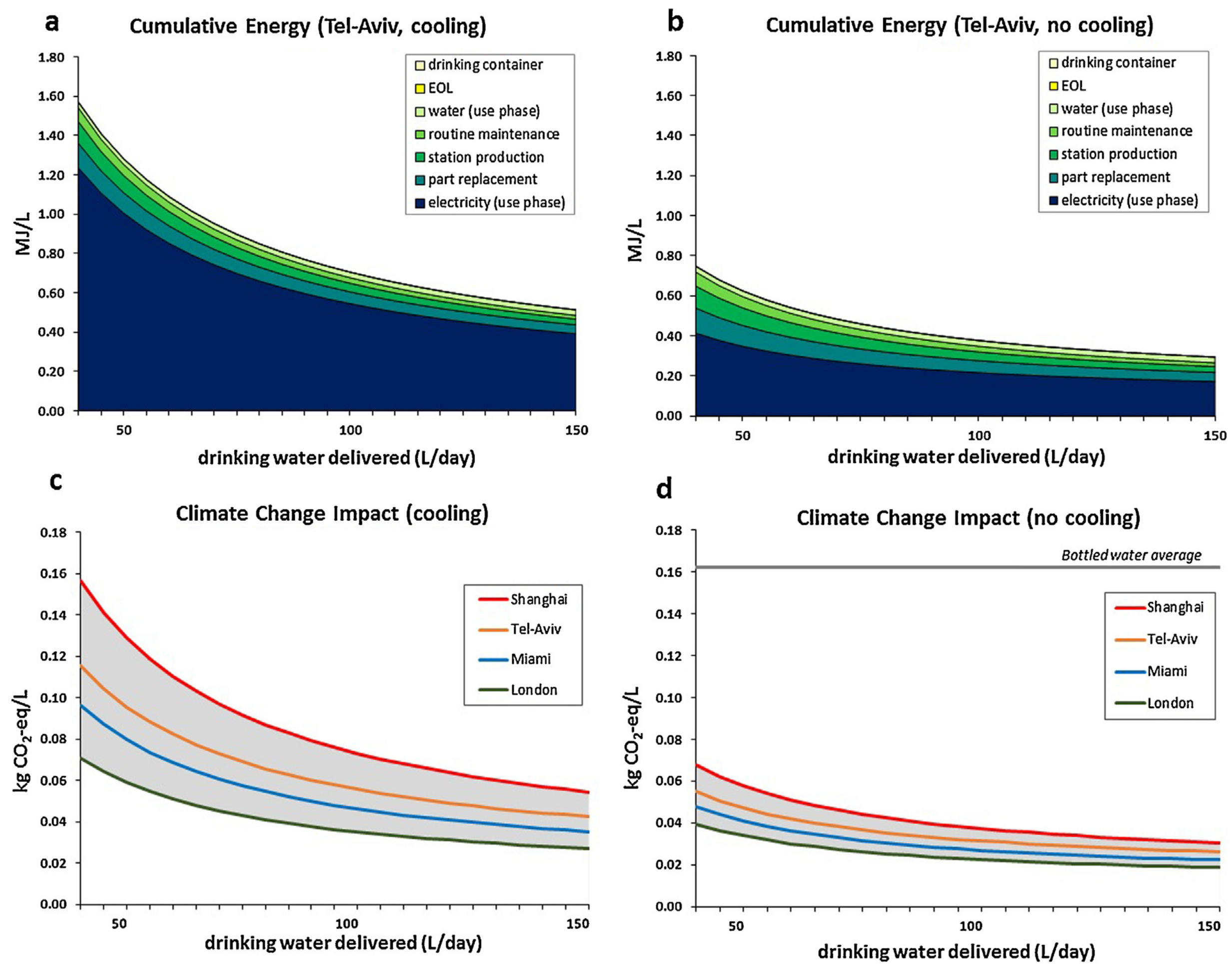

Fig. 2. Woosh station per liter CED and GHG emissions as a function of water volume consumed daily for cooled (panels a,c) and room temperature (panels b,d) scenarios. In the CED cases (panels a,b) the colored layers represent each component's contribution to overall energy demand in ascending order. 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 (from top tp bottom) – Chinese grid (red), Israeli grid (orange), 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. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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	t CO_2-eq	GJ	kg CO_2-eq/L	MJ/L	t 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

ple through the supply chain, reducing environmental pressures related to transportation, storage and end of life treatment.

One 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 even under an extreme case where all the bottled water currently consumed in Israel were instead delivered, chilled from water stations the required electricity would amount to less than 1% of daily peak demand (Ministry of National, 2015)

Ultimately, from a policy perspective it would seem that even at a low consumption level 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

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 (i.e. the daily amount of water provided by the station) 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.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2016.11.010.

References

Ashby, M.F., 2012. Materials and the Environment: Eco-Informed Material Choice. Elsevier.
Barrios, R., Siebel, M., van der Helm, A., Bosklopper, K., Gijzen, H., 2008. Environmental and financial life cycle impact assessment of drinking water production at Waternet. J. Clean. Prod. 16, 471–476.
Beckman, D.S., 2014. The Threats to Our Drinking Water. The New York Times, New York.
Beverage Marketing Corporation, 2014. Bottled Water Sustains Strength.
Bilec, M., Ries, R., Matthews, H., Sharrard, A., 2006. Example of a hybrid life-cycle assessment of construction processes. J. Infrastruct. Syst. 12, 207–215.
Botto, S., Niccolucci, V., Rugani, B., Nicolardi, V., Bastianoni, S., Gaggi, C., 2011. Towards lower carbon footprint patterns of consumption: the case of drinking water in Italy. Environ. Sci. Policy 14, 388–395.
Botto, S., 2009. Tap Water vs. Bottled Water in a Footprint Integrated Approach. Available from Nature Precedings, http://hdl.handle.net/10101/npre.2009.3407.1.
City of Miami Beach, 2016. Execute agreement: Citywide network of smart drinking water stations. City of Miami Beach. : offical website.
DECC, 2016. UK Energy Statistics, 2015 & Q4 2015. In: Change DoEaC, editor.
Daniels, M.C., Popkin, B.M., 2010. Impact of water intake on energy intake and weight status: a systematic review. Nutr. Rev. 68, 505–521.
Dettling, J, Tatti, E, Ace, J., 2010. Environmental life cycle assessment of drinking water alternatives and consumer beverage consumption in North America. North America Project Report.
Dettore, C.G., 2009. Comparative life-cycle assessment of bottled vs. tap water systems. Ann Arbor.
EIA, 2016. Table 5. Electric power industry generation by primary energy source, 1990 through 2014 2016 ed: U.S. Energy Information Administration.
Fantin, V., Scalbi, S., Ottaviano, G., Masoni, P., 2014. A method for improving reliability and relevance of LCA reviews: the case of life-cycle greenhouse gas emissions of tap and bottled water. Sci. Total Environ. 476–477, 228–241.
Franklin Associates, 2009. Life Cycle Assessment of Drinking Water System: Bottle Water, Tap Water, and Home/Office Delivery Water. Revised Final peer-reviewed LCA report, 2009. 09-LQ-104 22 October 2009.
Friedrich, E., Pillay, S., Buckley, C., 2009a. Carbon footprint analysis for increasing water supply and sanitation in South Africa: a case study. J. Clean. Prod. 17, 1–12.
Friedrich, E., Pillay, S., Buckley, C., 2009b. Environmental life cycle assessments for water treatment processes a South African case study of an urban water cycle. Water SA 35, 73–84.
Friedrich, E., 2002. Life-cycle assessment as an environmental management tool in the production of potable water. Water Sci. Technol. 46, 29–36.
Ganim, S, Tran, L., 2016. How tap water became toxic in Flint, Michigan.CNN.com.
Grady, C., Younos, T., 2012. Bottled water technology and its global ramifications: an overview. Int. Water Technol. J. 2, 185–194.
Hendrickson, C., Horvath, A., Joshi, S., Lave, L., 1998. Peer reviewed: economic input–output models for environmental life-cycle assessment. Environ. Sci. Technol. 32, 184A–191A.
Hu, Z., Morton, L.W., Mahler, R.L., 2011. Bottled water: United States consumers and their perceptions of water quality. Int. J. Environ. Res. Public Health 8, 565–578.
Huijbregts, M.A., Rombouts, L.J., Hellweg, S., Frischknecht, R., Hendriks, A.J., van de Meent, D., et al., 2006. Is cumulative fossil energy demand a useful indicator for the environmental performance of products? Environ. Sci. Technol. 40, 641–648.
IBWA, 2016. PET facts.
IEA, 2016a. China: Electricity and Heat for 2013. International Energy Agency.
IEA, 2016b. Israel: Electricity and Heat for 2013. International Energy Agency.
Jéquier, E., Constant, F., 2010. Water as an essential nutrient: the physiological basis of hydration. Eur. J. Clin. Nutr. 64, 115–123.
Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., et al., 2015. Plastic waste inputs from land into the ocean. Science 347, 768–771.
Joshi, S., 1999. Product environmental life-cycle assessment using input-output techniques. J. Ind. Ecol. 3, 95–120.
Jungbluth, N., 2006. 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.
Kang, D., Auras, R., Singh, J., 2017. Life cycle assessment of non-alcoholic single-serve polyethylene terephthalate beverage bottles in the state of California. Conserv. Recycl. 116, 45–52.
Lagioia, G., Calabrò, G., Amicarelli, V., 2012. Empirical study of the environmental management of Italy's drinking water supply. Conserv. Recycl. 60, 119–130.
Lenzen, M., 2000. Errors in conventional and input-output–based life–cycle inventories. J. Ind. Ecol. 4, 127–148.
Majeau-Bettez, G., Stromman, A.H., Hertwich, E.G., 2011. Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues. Environ. Sci. Technol. 45, 10170–10177.
Mann, L., 2013. Study finds nearly half of Americans not drinking enough water. Chicago Tribune. Chicago Tribune website.
Matthews, H.S., Small, M.J., 2000. Extending the boundaries of life-cycle assessment through environmental economic input-output models. J. Ind. Ecol. 4, 7–10.

Meylan, G., Ami, H., Spoerri, A., 2014. Transitions of municipal solid waste management. Part II: hybrid life cycle assessment of Swiss glass-packaging disposal. Resources. Conserv. Recycl. 86, 16–27.
Ministry of National Infrastructure Energy & Water Resources, 2015. Israel.
Murray, A., Horvath, A., Nelson, K.L., 2008. Hybrid life-cycle environmental and cost inventory of sewage sludge treatment and end-use scenarios: a case study from China. Environ. Sci. Technol. 42, 3163–3169.
Nessi, S., Rigamonti, L., Grosso, M., 2012. LCA of waste prevention activities: a case study for drinking water in Italy. J. Environ. Manage. 108, 73–83.
Nestlé Waters, 2010. Nestlé Waters – Creating Shared Value Report 2005–2010.
Nick, S., 2010. Italy Bans the Plastic Water Bottle Along Heritage Coastline. The Telegraph, UK.
Parker, L., Burns, A.C., Sanchez, E., 2009. Local Government Actions to Prevent Childhood Obesity. National Academies Press.
Polizzi di Sorrentino, E., Woelbert, E., Sala, S., 2016. Consumers and their behavior: state of the art in behavioral science supporting use phase modeling in LCA and ecodesign. Int. J. Life Cycle Assess. 21, 237–251.
Sima, L.C., Elimelech, M., 2013. More than a drop in the bucket: decentralized membrane-based drinking water refill stations in southeast Asia. Environ. Sci. Technol. 47, 7580–7588.
Tarantini, M., Ferri, F., 2003. A life cycle assessment study of the environmental sustainability of domestic water saving techniques. Sustain. Plann. Dev. 6, 579–589.
Tenne, A., 2010. Sea Water Desalination in Israel: Planning, Coping with Difficulties, and Economic Aspects of Long-Term Risks.
Torretta, V., 2013. Environmental and economic aspects of water kiosks: case study of a medium-sized Italian town. Waste Manage. 33, 1057–1063.
Unicef and world health Organization, 2014. Progress on Sanitation and Drinking Water: Update, World Health Organization.
Vince, F., Aoustin, E., Bréant, P., Marechal, F., 2008. LCA tool for the environmental evaluation of potable water production. Desalination 220, 37–56.
Wendy, K., 2010. Battle Brews over Bottled Water. USA Today.
Williams, E.D., Weber, C.L., Hawkins, T.R., 2009. Hybrid framework for managing uncertainty in life cycle inventories. J. Ind. Ecol. 13, 928–944.