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Energy implications of bottled water

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Abstract
As bottled water use continues to expand around the world, there is growing interest in the environmental, economical, and social implications of that use, including concerns about waste generation, proper use of groundwater, hydrologic effects on local surface and groundwater, economic costs, and more. A key concern is how much energy is required to produce and use bottled water. This paper estimates the energy footprint required for various phases of bottled water production, transportation, and use. We do not develop a single comprehensive life-cycle energy estimate because of differences among water sources, bottling processes, transportation costs, and other factors, but we quantify key energy inputs necessary for site-specific assessments. We also apply these inputs to three site-specific examples of the energy required from production to the point of use: local bottled water produced and used in Los Angeles, water bottled in the South Pacific and shipped by cargo ship to Los Angeles, and water bottled in France and shipped in various ways to Los Angeles. For water transported short distances, the energy requirements of bottled water are dominated by the energy used to produce the plastic bottles. Long-distance transport, however, can lead to energy costs comparable to, or even larger than, those of producing the bottle. All other energy costs—for processing, bottling, sealing, labeling, and refrigeration—are far smaller than those for the production of the bottle and transportation. These data can be used to generate specific estimates for different sources, treatments, and delivery options.

Keywords: bottled water, energy

1. Introduction

The consumption of ‘bottled water’—fresh water sold in individual consumer-sized containers—is growing rapidly. In 2007, the last year for which detailed global data were available, more than 200 billion liters of bottled water were sold, largely in North America and Europe, but with rapidly expanding sales in many developing countries as well. During that same year, the Beverage Marketing Corporation, which tracks beverage sales, estimated that consumers in the United States purchased over 33 billion liters of bottled water or an average of over 110 liters (nearly 30 gallons) per person. Bottled water sales have increased by 70% since 2001 in the United States, and have now far surpassed the sales of milk and beer (table 1). The only beverage category with larger sales is carbonated soft drinks (CSDs). Furthermore, per-capita bottled water consumption is growing, while per-capita sales of milk and CSDs are falling (Martinez 2007).

In the United States, the Food and Drug Administration (FDA) has established regulations that specify how bottled water can be labeled, depending on its source[1]. While there are many different kinds of bottled water, two dominate the market: ‘spring water’ and ‘purified water’. According to US Food and Drug Administration regulations: ‘purified water’ includes municipal tap water that has received further treatment through ‘distillation, deionization, reverse osmosis or other

Table 1. Sales of major beverages in the United States, 2006. (Source: California Energy Commission 2007, note: 2007 sales of bottled water exceeded 33 million liters.)

Beverage	Million liters
Carbonated soft drinks (regular and diet)	57 169
Bottled water (95% still and 5% sparkling)	31 238
Beer	24 489
Milk	21 476

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[1] Title 21 of the *Code of Federal Regulations* (21 *CFR*). ‘Standard of identity’ labeling regulations are found in Title 21 *CFR* section 165.110[a], US Government Printing Office. Washington, DC.

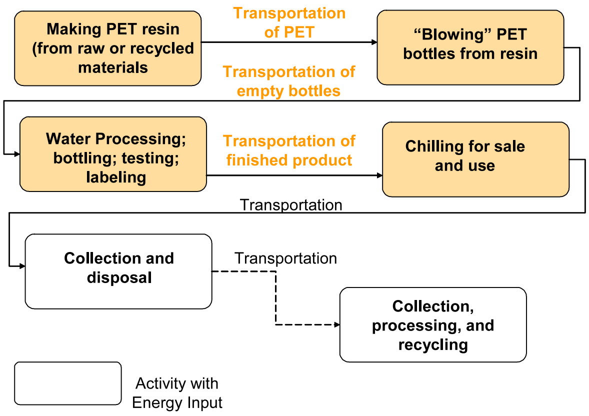

Figure 1. Flow diagram showing examples of where energy is required during bottled water manufacturing, use, and disposal. There is energy associated with each major life-cycle stage and additional energy required with each transportation action. We evaluate the energy required in the first four stages, including transportation (colored orange) between them. Energy for waste collection, disposal, and recycle was not computed here, but is likely to be a small fraction of the first several stages.

suitable processes'. 'Spring water' is water 'derived from an underground formation from which water flows naturally to the surface of the earth . . . collected only at the spring or through a bore hole tapping the underground formation feeding the spring . . .'.

In 2006 in the United States, approximately 44% of all bottled water originated as municipal water and is sold as 'purified' water, with the remaining 56% coming from protected springs or groundwater. Most of the purified water sales come from the three largest producers of bottled water: the Coca-Cola Company (maker of Dasani), the Pepsi Cola Company (maker of Aquafina), and Nestlé (maker of Pure Life and other brands) (Hemphill 2007). Nestlé is also the largest US producer of spring water.

Bottled water is purchased by consumers for a wide variety of reasons, ranging from convenience to worry over the availability and quality of potable water from municipal systems. We will not discuss the broad controversy over the appropriateness of bottled water use in this paper, but we note the backlash that has developed among some consumers, restaurants, and even municipalities over the societal and environmental costs of bottled water in recent years. Among the issues of public concern are the impacts of water extractions on local watersheds, equity issues associated with commercializing a public resource, the environmental consequences of producing and disposing of plastic bottles, and the energy (and greenhouse gas emissions that result) required to bottle water. We address the issue of energy here.

2. Energy to produce bottled water

Energy is required to make, package, transport, chill, use, and recycle bottled water and its packaging (see figure 1). The total amount of energy needed is complicated by many factors, including the location and type of the water source, the distance from the bottler to the consumer, the types of material and packaging used, the method of transportation, and much more. This paper computes the energy required to bring the water to the consumer, including specifically the energy to make the plastic materials used in bottles, fabricate that plastic into the actual bottles, process the water prior to bottling, fill and seal the bottle, transport the product to the end user, and chill it for use. Rather than compute a single energy factor for bottled water, we offer three examples of bottled water energy requirements from production to point of sale.

Figure 2. Recycling code for polyethylene terephthalate (PET). These codes, introduced in 1988 by the plastics trade association (the Society of the Plastics Industry, Inc.), help consumers identify and recycle different forms of plastics.

2.1. Energy required to manufacture plastic bottles

Bottled water is sold in containers ranging from small 8 ounce or half liter containers popular in school lunches to the multi-gallon bottles used in home and office water coolers. The vast majority of single-use plastic water bottles are made out of polyethylene terephthalate (PET). PET is a thermoplastic polymer resin used for a wide variety of purposes, ranging from the production of polyester fibers and clothing to food and beverage containers. In the United States, PET is easily recognized by the recycling code '1' (figure 2), which is imprinted on the bottle to help consumers identify and recycle different forms of plastics. As the container volume increases, bottlers are more likely to switch from PET to polycarbonate, which has greater rigidity at large sizes and requires approximately 40% more energy to produce than bottle-grade PET (Bousted 2005).

Manufacturing PET bottles requires combining ethylene glycol and terephthalic acid to produce PET resin in the form of small pellets that resemble rice. These pellets are then melted and injected into a mold to produce a 'preform'—a thick-walled test tube with a finished neck and set of cap threads. The preform is then heated, stretched, and blown into the final bottle shape. Some major bottlers blow their own bottles from preforms, though many smaller bottlers purchase pre-blown bottles produced offsite and transported to the bottling plant.

Energy is embodied in PET material itself, and additional energy is required to turn PET into bottles. This energy is typically supplied by natural gas and petroleum, along with electricity from the local electricity grid. Two comprehensive life-cycle assessments for producing PET and PET bottles have been completed, which indicate that the energy required to produce PET resin is approximately 70–83 MJ (thermal) kg^{-1} of PET resin (Bousted 2005, Franklin Associates 2007)[2].

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[2] All energy units here are thermal, unless otherwise specified as electrical (e.g., $\text{kWh}_{(\text{e})}$). All conversions of thermal to electrical assume an efficiency of 0.33, i.e., 3 kWh (thermal) equal 1 kWh (electrical).

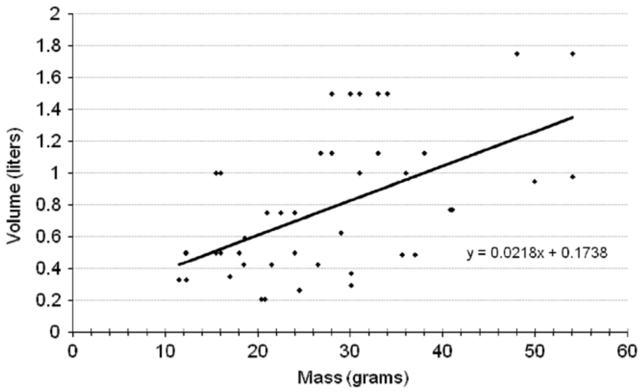

Figure 3. Plot of mass versus volume for a range of PET water bottles, excluding the weight of the closure or any waste. Solid line is a linear regression on the data. Some bottlers are moving toward lighter bottles to reduce production and transportation costs and waste volume. These data came from a survey of all the major bottled water brands by the Pacific Institute.

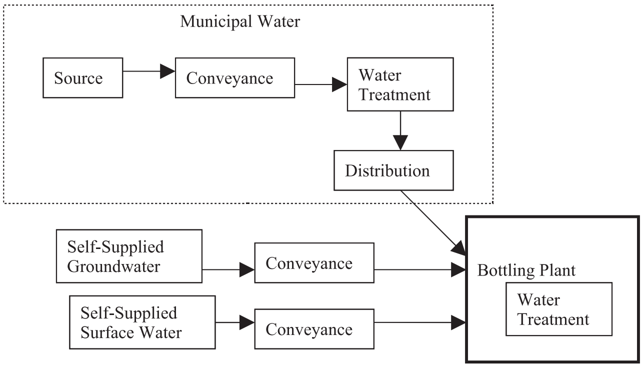

Figure 4. Typical process diagram for bottling water from a municipal or spring water source.

Producing preforms and turning them into bottles requires an additional 20 MJ kg^{-1} of finished bottle. The total energy used in producing PET bottles, including some transportation energy to move the resin to the point where bottles are produced and then filled, is thus about 100 $MJ_{(th)}$ kg^{-1} or 100 000 $MJ_{(th)}$/ton of PET.

The mass of PET required per bottle depends on the style, thickness, and size of the bottle. Figure 3 shows a wide range of water bottle volumes and masses as reported by PET manufacturers. A linear regression on these data shows that an average 1 l bottle weighs approximately 38 g, excluding the cap, which typically weighs an additional 2 g.

Some manufacturers have launched new efforts to reduce the amount of PET required to make a water bottle. In 2007, Logoplaste Group in Portugal announced a new line of lightweight preforms with a 0.33 l bottle weighing 11.5 g (35 g l^{-1}) (Pittman 2006). Nestlé produces a lightweight half liter bottle weighing 12.2 g (or around 24.4 g l^{-1}) and is experimenting with the production of a 1.5 l PET bottle weighing between 28 and 33 g (or between 18 and 22 g l^{-1}). The Coca-Cola Company recently introduced a new 20 ounce bottle weighing 18.6 g (or around 31.5 g l^{-1}).

Combining the estimate of the energy required to make PET and form it into bottles with the average weight-to-volume data results in a manufacturing energy cost of around 4.0 MJ per typical 1 l PET bottle weighing 38 g. This estimate includes the energy required to convert raw materials into PET resin, energy required to turn resin into bottles ready for filling, and energy to transport PET or bottles to the filling plant.

If all bottled water required an average of 38 g of PET per liter, approximately 3.8 million tons of PET were required to produce the 100 billion liters of bottled water containers sold worldwide in 2007. If all bottled water producers shifted toward the lightest bottles, PET production could be reduced by around 30%. These estimates exclude any PET waste generated during bottle production or used for the packaging (such as the label, carton, or plastic wrapping) of the final retail product. Because beverage companies are only slowly reducing the weight of their bottles, we estimate that approximately one million tons of PET were produced to make the plastic bottles consumed in the United States in 2007 and three million tons were produced globally. Producing the PET bottles to satisfy global bottled water demand thus required approximately 300 billion $MJ_{(th)}$ of energy (three million tons of PET times 100 000 $MJ_{(th)}$/ton). Given that a barrel of oil contains around 6000 MJ, this is the energy equivalent of approximately 50 million barrels of oil per year[3]. The use of recycled materials could lead to additional energy savings but almost all plastic bottles for water are currently made from virgin PET.

2.2. *Energy to process bottled water*

Energy is also required to prepare water for bottling. Bottled water comes from two primary sources: municipal water systems (tap water) and surface and groundwater systems. In the United States, municipal water can be bottled with or without additional treatment at the bottling plant. Municipal water that is bottled without additional treatment must be labeled ‘municipal water’, whereas municipal water that has received additional processing can be labeled as ‘purified’. Purified water is thus typically treated twice, first by the municipality to meet national standards under the Safe Drinking Water Act and then by the bottler (figure 4). In this study, we limit our analysis to include energy required to process water at the bottling plant (the heavily outlined box shown in figure 4). As shown below, our results indicate that the energy requirements for processing water, even extensive processing, are small relative to the energy associated with the plastic bottle and its production.

Both ‘purified’ municipal and ‘spring’ water are typically treated at the bottling plant. The level of treatment varies depending on the source water quality, the category of bottled water, and preferences of the bottling company. Although spring water is not supposed to undergo treatment that substantially changes its chemical composition, it often undergoes some processing at the bottling plant. Treatment processes can include micro or ultrafiltration, ozonation,

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[3] Not all the energy used to make these bottles is oil, or even fossil fuels; thus we use the common comparison of ‘energy equivalent’.

Table 2. Energy requirements for water-treatment methods.

Treatment technique	Energy use (kWh_e/million liters)	Data source
Ozone		
Pre-oxidation (pre-treatment)	30	SBW Consulting, Inc (2006)
Disinfection	100	SBW Consulting, Inc (2006)
Ultraviolet (UV) radiation (medium pressure)		
Bacteria	10	SBW Consulting, Inc (2006)
Viruses	10–50	SBW Consulting, Inc (2006)
Microfiltration/ultrafiltration	70–100	SBW Consulting, Inc (2006)
Nanofiltration (source TDS = 500–1000 ppm)	660	AWWA (1999)
Reverse osmosis		
Source TDS = 500 ppm	660	AWWA (1999)
Source TDS = 1000 ppm	790	AWWA (1999)
Source TDS = 2000 ppm	1060	AWWA (1999)
Source TDS = 4000 ppm	1590	AWWA (1999)
Seawater desalination (reverse osmosis)	2500–7000	National Research Council (2008)

ultraviolet radiation, and reverse osmosis. As shown in table 2, energy requirements vary considerably among the various water-treatment techniques. Disinfecting water with ultraviolet radiation, for example, requires as little as 10 kWh_e/million liters (SBW Consulting, Inc 2006). Energy requirements for reverse osmosis, however, can be as high 1600 kWh_e/million liters for source water with a total dissolved solids concentration of 4000 ppm (AWWA 1999) and even higher for desalinating seawater. Several companies worldwide are selling bottled water desalinated from seawater.

Typical treatment at a bottling plant includes all or some combination of the following methods: ultraviolet radiation, micro or ultrafiltration, reverse osmosis, and ozonation. No public data are available on the number of bottling plants that employ the various treatment methods. Thus, the energy requirements for treating most municipal or spring waters at the bottling plant range from 10 kWh_e/million liters for simple ultraviolet radiation alone to as high as 1800 kWh_e per million liters for treatment involving UV, filtration, ozone, and reverse osmosis. Even extensive treatment, therefore, requires only between 0.0001 and 0.02 $MJ_{(th)}\ l^{-1}$, a small fraction of the energy embedded in the PET bottle itself. Although not included here, we note that there are additional energy requirements for capturing, conveying, and/or treating water prior to entering the bottling plant. The average energy intensity of municipal water in Southern California, for example, is about 3000 kWh_e/million liters (0.03 $MJ_{(th)}\ l^{-1}$) (California Energy Commission 2005).

2.3. Energy to clean, fill, seal, and label bottles

Following the production of the bottles and the treatment of the water, machines then rinse, fill, cap, and label PET bottles. A review of energy specifications from nine major manufacturers shows that typical machines use between 0.002 and 0.01 $MJ_{(th)}$ per bottle for machines that handle between 3000 and 39 000 bottles per hour. The average machine can clean, fill, and seal around 15 000 bottles per hour and requires 0.006 $MJ_{(th)}$ per bottle[4]. High-volume labeling and packaging machines, such as those produced by Sacmi Industries, can label 36 000–42 000 bottles per hour using 27 $kWh_{(e)}\ h^{-1}$,[5] or around 0.008 $MJ_{(th)}$ per bottle. Thus, the total energy required to clean, fill, seal, label, and package bottled water is around 0.014 $MJ_{(th)}$ per bottle, or only about a third of a per cent (0.34%) of the energy embodied in the bottle itself.

2.4. Energy to transport bottled water

After the production of bottled water, energy is required to move the finished product to markets. Because water is heavy—weighing one metric ton per cubic meter—energy associated with transporting bottled water can be significant. The total transportation energy requirements depend on two major factors: the distance from the bottling plant to the market and the mode of transportation.

Numerous government energy and transportation ministries, including the US Department of Energy, the US Department of Transportation, the European Union, and Natural Resources Canada, have compiled and analyzed data on the energy costs of different modes of freight transportation. Table 3 summarizes typical transportation energy-intensity values for major modes of freight transportation in megajoules per metric ton of cargo per kilometer transported. Air cargo is by far the most energy intensive mode of transportation; truck transportation is more energy intensive than transportation by rail or bulk ocean shipping.

The distance from the bottling plant to the final point of consumption varies significantly with the type of bottled water. From a practical point of view, ‘purified water’ is usually produced by treating and packaging municipal water in major demand centers close to markets. These products are bottled at local bottling plants spread across the country near major urban areas, with deliveries to local markets. The Coca-Cola Company, the PepsiCo, and other major bottlers produce treated municipal waters in many major cities for local distribution, often at the same plants producing soft drinks and other beverages.

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[4] We assume here an average ratio of 3 kW (thermal)/kW (electrical) and all energy use totals are presented as thermal equivalents.

[5] Reported power requirements for a Sacmi beverage bottle labeler. Personal communication, Sacmi Industries, http://group.sacmi.com/beverage-and-packaging/cold-glue-labellers.htm

Table 3. Transportation energy costs. (Note: all values in units of megajoules per ton cargo per kilometer (MJ t^{-1} km^{-1}). Heavy trucks are used for long-distance and inter-city freight transport. Medium trucks are used for intra-city freight delivery. Sources: US Department of Energy 2007; Natural Resources Canada 2007.)

Cargo ship/ocean (MJ t^{-1} km^{-1})	Air cargo (MJ t^{-1} km^{-1})	Rail (MJ t^{-1} km^{-1})	Heavy truck (MJ t^{-1} km^{-1})	Medium truck (MJ t^{-1} km^{-1})
0.37	15.9	0.23	3.5	6.8

Table 4. Transportation scenarios for bottled water consumed in Los Angeles Metropolitan region with distances by mode of transport. (Note: heavy trucks are used for long-distance and inter-city freight transport. Medium trucks are used for intra-city freight delivery.)

Scenario	Medium truck (km)	Heavy truck (km)	Rail (km)	Cargo ship (km)	Total energy cost (MJ l^{-1})
Local production	200 (local delivery)	0	0	0	1.4
Spring water from Fiji	100 (local delivery)	0	0	8900 (Fiji to Long Beach)	4.0
Spring water from France	100 (local delivery)	600 (Evian to Le Havre)	3950 (New York to Los Angeles)	5670 (Le Havre to New York)	5.8

In contrast, 'spring' waters are usually packaged at specific, single sources and transported, sometimes significant distances, to points of demand. Nestlé, for example, bottles water under the Arrowhead label at plants in Southern California for distribution throughout their western markets and bottles water under the Poland Spring label in Maine for distribution in eastern markets. More extreme examples include Fiji Spring Water, which is packaged at the source in the South Pacific, or Evian water, which is packaged at the source in France and then shipped to markets around the world.

Energy requirements for transportation can be evaluated using data in table 3 and assumptions about the distance traveled. We evaluated three different transportation scenarios for products shipped to the major Los Angeles, California market: (1) processed municipal water that is distributed locally by truck; (2) spring water produced in the South Pacific (such as Fiji Spring Water), transported by ship to Los Angeles, and distributed locally by truck; and (3) spring water packaged in France (such as Evian), shipped to the eastern United States, transported by freight railcars to Los Angeles, and distributed locally by truck.

The transportation energy cost varies significantly among these scenarios (table 4), and will vary with different assumptions about distance and transport mode. The scenarios summarized in table 4, however, represent the approximate minimum and maximum energy costs, unless bottled water is shipped any distance by air. Locally packaged and marketed purified bottled water, delivered within 200 km of a bottling plant by truck has a total transportation energy cost of around 1.4 MJ l^{-1}. Spring water transported across the Pacific from Fiji to Los Angeles and then delivered locally within 100 km has a total transportation energy cost of 4.0 MJ l^{-1}. French spring water shipped by truck from the source to French ports, by ship across the Atlantic, by train from the East Coast of the US to Los Angeles, and then locally by truck has a transportation energy cost of around 5.8 MJ l^{-1}.

2.5. *Energy to cool bottled water prior to use*

Energy is also required to cool the bottled water prior to sale or consumption. There are two components to this—the energy to cool the water from room temperature to the temperature of the refrigerator or commercial display cooler, and the energy to maintain the cold water until it is sold. For the first component, we estimate that bottled water is cooled from a room temperature of around 20.0 °C to a typical refrigerator or cooler temperature of around 3.3 °C. Given that the specific energy of water is around 4.2 kJ kg^{-1} K^{-1}, we estimate that cooling 1 l of water 17 °C requires 220 kJ, or 0.2 MJ l^{-1}.

The second component depends on the length of time the bottled water is kept cool before consumption and the energy performance of the refrigerator. As of October 2008, more than 1000 refrigerators met the US Energy Star standards for efficiency. These refrigerators had an average volume of 17 cubic feet and used 450 $kWh_{(e)}$ per year or around 8.65 $kWh_{(e)}$ per week. No data are available on the time the average consumer chills bottled water before consuming, but if we assume that a consumer keeps a liter of bottled water cold for a week before consuming it, then the energy required to maintain the cool bottle is another 0.2 MJ l^{-1}.

2.6. *Summary of energy uses*

Table 5 summarizes the total energy requirements for capturing, conveying, and treating bottled water, producing the plastic bottles, and cooling the water prior to sale, given a set of explicit assumptions. For this analysis, we assume that water enters the bottling plant from municipal or self-supplied surface and groundwater, excluding energy associated with long-distance transportation in pipelines or aqueducts, or from deep pumping. Once at the bottling plant, water undergoes additional treatment from a range of processes that can include microfiltration, ozonation, ultraviolet radiation, and reverse osmosis and put into PET bottles, capped, labeled, and packaged. It is then shipped to consumers and may be cooled in refrigerators before use. Based on these assumptions,

Table 5. Total energy requirements for producing bottled water. (Note: we assume here an average ratio of three kWh (thermal) per kWh (electrical) and 3.6 MJ kWh^{-1}.)

	Energy intensity ($\mathrm{MJ}_{(\mathrm{th})}$ l^{-1})
Manufacture plastic bottle	4.0
Treatment at bottling plant	0.0001–0.02
Fill, label, and seal bottle	0.01
Transportation: range from three scenarios	1.4–5.8
Cooling	0.2–0.4
Total	5.6–10.2

the total energy required for bottled water will typically range from 5.6 to 10.2 MJ l^{-1}. In comparison, producing tap water typically requires about 0.005 MJ l^{-1} for treatment and distribution (Burton 1996). Our analysis indicates that for water transported short distances, the energy requirements of bottled water are dominated by the energy to produce the plastic bottles. Long-distance transport, however, can lead to energy costs equal to the energy to produce the bottle. All other energy costs—for processing, bottling, sealing, labeling, and refrigeration—are far smaller.

3. Conclusions

This paper estimates the energy footprint required for various phases of bottled water production, transportation, and use. For water transported short distances, the energy requirements of bottled water are dominated by the energy to produce the plastic bottles. Long-distance transport, however, can lead to energy costs comparable to, or even larger than, the energy to produce the bottle. Far less energy is needed for processing and treating the water, and cooling bottles for retail sale. We did not evaluate waste disposal here. Transportation costs are highly variable, ranging from 1.4 MJ for water produced within 200 km of the consumer market to 5.8 MJ for water produced in France and sold in Los Angeles. Combining all of the energy inputs totals, we estimate that producing bottled water requires between 5.6 and 10.2 MJ l^{-1}—as much as 2000 times the energy cost of producing tap water. Given an annual consumption of 33 billion liters of bottled water in the US, we estimate that the annual consumption of bottled water in the US in 2007 required an energy input equivalent to between 32 and 54 million barrels of oil or a third of a per cent of total US primary energy consumption. We estimate that roughly three times this amount was required to satisfy global bottled water demand.

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