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Emily Diaz-Loar

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Emily Diaz-Loar
Ph.D. Candidate
Department of Economics
University of Massachusetts Amherst

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ABSTRACT

As of the most recent 2018 data, U.S. residents purchased more than 70 billion plastic water bottles. On average, this amounts to each U.S. resident buying 214 plastic water bottles during 2018. Virtually all these bottles are manufactured as fossil fuel-based products, and 86 percent are disposed of after only one use. Such fossil fuel-based single-use plastic bottles inflict a range of severe negative impacts on the environment and human health. They leach toxic chemicals into the soil, water and food supply, which in turn contribute to causing various types of cancers as well as infertility, in humans and other species. They also release tiny 'microplastic' particles, which have been found in, among other parts of the human body, the carotid artery tissues that supply blood to the brain. Recent research has found that people with microplastics in their carotid artery tissues were twice as likely to have a heart attack, stroke or die from any cause over the next three years than people who had none. Beyond this, plastic bottles litter beaches and roadways, clog water drains, strangle animals and contaminate habitats.

It is clear that continuing, and expanding, the consumption of single-use fossil fuel-based plastic water bottles, in the U.S. and elsewhere, is unsustainable. In this study, I examine alternative approaches to phasing out their use. More specifically I consider six possible alternatives to single-use fossil fuel-based plastic water bottles within the U.S. economy. These include: recycling fossil-fuel based bottles; utilizing plants as the raw material for producing 'bioplastic' bottles; and producing bottles with materials other than plastics, including paperboard cartons; glass; aluminum; and stainless steel. Of these alternatives, I show that, in terms of both environmental impacts and production costs, the most viable substitutes for single-use fossil-fuel based plastic bottles are reusable bottles made from either aluminum or stainless steel. Overall, aluminum or stainless steel-based bottles can significantly reduce the environmental impacts of water bottles, in particular the chemical toxicity that results from their use. Substituting aluminum or stainless steel-based bottles can also dramatically reduce the levels of waste and raw material extraction associated with fossil fuel-based plastic bottles. Further, I estimate that the costs of producing bottles from either aluminum or stainless steel will fall by over 30 percent in a scenario in which they substitute for 90 percent of the fossil fuel-based single-use plastic bottles now being consumed in the U.S. Overall, my results demonstrate that there are realistic prospects to achieve major environmental and economic benefits through phasing out single-use plastic bottles and creating viable alternatives to their continued use.

1. INTRODUCTION

The first fossil fuel-derived plastic bottle was developed in 1973. Over the past 50 years, the use of plastic bottles has expanded exponentially, including as the predominant mode of packaging a variety of beverages. Water is currently their largest beverage application. In 2018, U.S. residents bought more than 70 billion single-use plastic water bottles. On average, this amounts to each U.S resident purchasing 214 plastic water bottles over 2018. This makes the U.S. the second-largest consumer of single-use plastic water bottles (after China, at 171.1 billion bottles in 2018), and the fourth-largest in terms of per capita consumption, after Mexico (446 bottles per person), Thailand (446 bottles per person) and Italy (309 bottles per person) (Rodwan Jr., 2019). As of 2022, the U.S. bottled water industry is valued at over $45 billion. This amounts to 15 percent of the global plastic water bottle. Assuming market conditions continue roughly along their current trajectory, the International Bottled Water Association projects that bottle consumption will grow at an average rate of about 7 percent yearly until 2050 (International Bottled Water Association, n.d. [a]).

Huge growth in plastic bottles has resulted in a range of severe environmental impacts. Within the U.S. economy, 86 percent of plastic bottles are disposed of after only one use (Aslani et al., 2021). As a result, plastic bottles occupy significant landfill space or end up as environmental pollution, littering beaches and roadways, clogging water drains, strangling animals, and contaminating habitats. Toxic chemicals used to produce the bottles in turn leach into the soil, water, and food supply, and are linked to a range of serious health impacts. Thus, a 2024 study by Raffaela et al. document that tiny 'microplastic' particles have been found in, among other parts of the human body, the carotid artery tissues that supply blood to the brain. This study indicated that people with microplastics in their carotid artery tissues were twice as likely to experience a heart attack, stroke or die from any cause over the next three years than people who had none (Raffaele et al., 2024).

These negative impacts from the widespread and persistently expanding use of single-use fossil fuel-based plastic bottles have motivated calls to limit or even eliminate their use. But, to date, no serious research has been conducted which considers viable approaches for phasing out the use of these plastic bottles and developing alternatives that can achieve major environmental benefits as well as economic gains in terms of lowering costs of producing the necessary supply of bottles.

In this study, I examine six possible alternatives to single-use fossil fuel-derived plastic water bottles within the U.S. economy. These include: bottles made from (1) recycled plastic, (2) bioplastic, (3) paperboard cartons, (4) glass, (5) aluminum, and (6) stainless steel. Of these, reusable aluminum and stainless-steel bottles are the most viable substitutes in terms of reducing environmental impacts as well as reducing the costs of supplying the necessary supply of bottles. These alternatives lessen the amount of waste that ends up in landfills and the environment, reduce raw material extraction and associated environmental impacts, and contribute less to harmful health effects from toxic chemicals. In addition, relative to a business-as-usual scenario through 2050, reusable aluminum and stainless-steel bottles reduce production costs by 46 percent when substituting 50 percent of plastic water bottles with reusable bottles; and by 34 percent, when substituting 90 percent of plastic water bottles. These results underscore the environmental and economic benefits associated with expanding reusable beverage containers. In doing so, this paper provides the environmental and economic justification for promoting reusable bottles in plastic policy initiatives.

This paper is organized as follows: The next section provides a history of single-use plastic water bottles, and the major factors which have contributed to their growth in the U.S. Section three reviews the environmental and health consequences of plastic water bottles. Section four assesses the technical, economic, and environmental characteristics of six potential substitutes, of which reusable aluminum and stainless-steel bottles are the most viable. Section five provides a direct comparison of the environmental impacts of reusable aluminum and stainless-steel bottles to the impacts from plastic bottles. Section six describes methodological details for estimating the substitution costs for two policy scenarios to reduce plastic water bottle consumption to 50 percent and 90 percent of business-as-usual projections from 2023 to 2050. Section 7 reviews the findings that demonstrate the environmental and economic benefits of transitioning to reusable aluminum and stainless-steel bottles. Section eight offers concluding remarks.

2. A HISTORY OF PLASTIC BOTTLED WATER

Since humans became adept at toolmaking, they have devised various ways to package and carry water. Before there was a formal market, humans used shells, ceramics, and carved wood or stone to carry liquids. In the early 1800s, producers in France began to package natural spring water in glass containers to sell across Europe and the U.S. For over a century, glass was the most common material for water packaging. The seeds of its decline were planted in the 1940s with the development of polyethylene terephthalate (PET), an exceptionally cheap, lightweight, and durable fossil fuel-derived polymer. By the 1950s, PET was commercialized, and quickly became the most widely used material for all manner of packaging. In 1973, advances in polymer science and stretch blow molding techniques enabled the fabrication of the first PET bottle (Bouhlel et al., 2023; Hawkins, 2017). For many years, PET bottles were used primarily for carbonated beverages. It wasn't until the 1990s that water became commonly packaged and sold in PET, yet today 97 percent of bottled water is packaged in the material (Lundell and Thomas, 2020; International Bottled Water Association, n.d. [b]).

Before the emergence of PET bottles, bottled water was an expensive luxury good, certainly not an option for everyday consumption. Bottled water was transformed into the most prevalent packaged beverage in the U.S. as the result of marketing which portrayed the product as necessary and healthy. For instance, research on the importance of hydration had emerged in the 1980s and medical professionals began to recommend daily hydration goals. This was used in some of the first advertisements for bottled water, which promoted 'hydration support' as the key rationale for carrying water at all times (Hawkins, 2017). This also coincided with growing concerns about the safety of tap water. In the 1980s, an earthquake in Mexico led to a series of cholera epidemics arising from contaminated water supplies. While the public crisis did not extend to the U.S., beverage companies capitalized on negative publicity about the capabilities of governments to provide drinkable water (Bouhlel et al., 2023). Commercials depicting bottled water as a safe alternative to tap water were widely broadcast, despite the fact that, generally speaking, U.S. public water has been safe since at least 1920 (Center for Disease Control, 2018).

A variety of other marketing tactics, including the introduction of novel products, such as pH-balanced water, mineral water, and more, further bolstered the growing industry (Hawkins, 2011).

Beyond this, the PET bottle itself was essential for the growth of bottled water. PET packaging is cheap to produce, lightweight and, unlike glass, does not easily break. These qualities prompted a consequential shift in consumer culture as producers declared that plastic packaging could be used once and then easily thrown away. Disposability was seen as a virtue, as structural changes in living and work environments, including more frequent car travel and the growth of drive-thru businesses, generated a rapidly growing demand for portability and convenience. Disposability also promoted continuous re-purchase of new water bottles, leading to higher profits for producers across the supply chain (Mah, 2022). The inherent characteristics of PET bottles were thus essential to the growth of bottled water. Despite this, the PET bottle was presented as no more than an innocuous container to support hydration (Hawkins, 2011). While simultaneously minimizing the impacts that PET bottles would incur, beverage companies successfully transformed bottled water from a luxury item into a commonplace product and the cornerstone of growth for the industry.

3. THE IMPACT OF PET PLASTIC BOTTLES

The production, consumption, and waste of PET bottles are associated with harmful environmental and health impacts across their lifecycle. While their environmental impacts, especially in terms of pollution, are well-documented, research on the quality of bottled water as compared to tap water is more recent. Despite industry claims, several studies find that plastic bottled water is generally inferior in quality to tap water in the U.S. (Raj, 2005; Bradley et al., 2023; Gleick, 2010). In an infamous case, the city of Cleveland compared *Fiji* water (a common bottled water brand) to public supplies and found that the bottled water contained six times more arsenic than public supplies. This discrepancy is primarily due to divergent regulatory standards. As a public good, tap water is strictly monitored by the U.S. Environmental Protection Agency (EPA). By contrast, bottled water is considered a 'fast moving consumer good' and is therefore regulated by the Food and Drug Administration (FDA). Not only does the FDA have lower quality standards than the EPA, but because there are numerous water products on the market, less than 60 percent undergo testing at all (Silva, 2024). Issues of water quality, however, are only a small piece of the larger damage inflicted by plastic water bottles.

PET bottles are harmful to human health due to the variety of unregulated and potentially carcinogenic or endocrine-disrupting chemicals used in their production. These chemicals leach from products once they are thrown away and while in use, especially if the bottle is used for long periods of time or left in hot temperatures. In other words, plastic bottles are not only marketed and sold as single-use products, but their chemical compositions make them potentially harmful for long-term reuse (Azoulay et al., 2019). For example, the industrial chemical bisphenol A (also known as BPA) was once widely used in plastic bottles to enhance durability. Since the 1990s, researchers were aware of the endocrine-disrupting effects of the chemical, but it wasn't until 2010 that it was banned from some plastic containers. Today, most plastic bottles are BPA-free, but other yet unregulated chemicals may present similar or worse harm (Environmental Working Group, 2008). Chemicals also leach from PET bottles after they are discarded, contaminating the soil, water, and food supply, and harming plant and animal life.

While chemical pollution from plastic bottles is widespread, bottle pollution in the environment, and especially oceans and coastal regions, is their most visible impact. More than 86 percent of PET bottles are thrown away after only one use. Less than 30 percent of PET packaging is recycled, so most bottles end up in landfills, incinerated, or dumped into the environment. Plastic bottles do not readily decompose, and can persist as pollution for up to 400 years (Aslani et al., 2021). Managing this pollution is a serious financial burden for local communities and may damage local industry and infrastructure (Barrowclough and Deere Birkbeck, 2020). Additionally, plastic bottles slowly degrade and release 'microplastic' particles into surrounding environments. These tiny particles remain for at least 100 years and have been found almost everywhere, including food, breast milk, the human brain and placenta. Recent studies find that microplastics harm reproductive and digestive health, and that people with microplastic in their carotid artery tissues were twice as likely to have a heart attack, stroke or die from any cause over the next three years than people who had none (Ragusa et al., 2021; Azoulay et al., 2019; Marfella Raffaele et al., 2024).

The production of PET plastic is also associated with climate change impacts. Fossil fuels enter plastics production in two ways: as main feedstock and primary energy source. Production accounts for 8 percent of global oil demand and is responsible for 4.5 percent of global greenhouse gas emissions. PET, as the second-most used polymer for packaging materials (after low-density polyethylene), is an important contributor to the sector's large carbon footprint (Stegmann et al., 2022). According to Duan et al. (2024), the total lifecycle emissions of PET was over 500 million Mt in 2020. Almost half of this stems directly from fossil fuel refining and polymerization, while the rest is generated during manufacturing (Duan et al., 2024). PET bottles, in particular, require additional energy for transportation and temperature-controlled storage. In a comparison of bottled water and tap water, Aslani et al. (2021) finds that the production and distribution of one liter of plastic bottled water required up to 2000 times more energy than the treatment and distribution of the same amount of tap water. The intensity of plastic bottle pollution and its impact on ecosystems, infrastructures, and human health is one of the key factors motivating global calls to limit the consumption single-use plastics.

4. ALTERNATIVES TO PET BOTTLES

There are two strategies to phase out PET water bottles. The first is to reduce demand for packaged water, regardless of the packaging material. Such efforts would include expanding the availability of water fountains and ensuring the safety of public water supplies, so that consumers can drink water without having to carry a bottle with them. Today, with frequent travel, long-distance commutes, and an emphasis on hydration for better health, limiting the use of packaged water is impractical and unlikely to generate widespread support. So, while expanding public infrastructures for water consumption is an essential public service and can play a role in transforming current norms of bottled water consumption, reducing demand for packaged water is not a viable strategy on its own (Willis et al., 2019; Becerra-Galicia, 2022). The issue of packaging and distributing water in portable, convenient, and less harmful containers therefore remains of critical importance.

The second strategy is to reduce demand for PET water bottles by replacing them with bottles made from alternative materials. There is precedent for this, since alternative materials were commonly used before the development of PET. Moreover, a variety of non-plastic bottles are increasingly marketed as substitutes. However, a large-scale substitution of PET water bottles is limited by lack of comprehensive analysis of the economic, technical, and environmental characteristics of alternative materials. This section investigates these characteristics for six alternative water packaging materials, including recycled PET, bioplastic, paperboard cartons, glass, aluminum, and stainless steel[1].

For each material, I provide a general review of the environmental impacts associated with their production and waste. This includes the CO2 emissions arising from production, chemical toxicity, and waste generation and pollution. Although CO2 emissions could be mitigated by switching to renewable energy sources, the International Energy Agency (IEA) reports that for many of these materials progress in switching to renewables is modest, and the most effective way to minimize impacts is through recycling. Thus, for each material I also discuss the prospects for recycling, as a strategy to mitigate the impacts stemming from production and minimize waste generation and pollution. Furthermore, I review the technical characteristics of each material for bottle manufacture and their capacities to be reused. This section also provides an overview of the market structures and economic challenges to expanding production for each material.

Recycled PET

Industry and governments alike emphasize recycled PET (rPET) as an alternative to the virgin PET used in plastic bottles[2]. Policy efforts and corporate pledges to increase recycled content in plastic bottles are motivated by the apparent environmental benefits of rPET as compared to virgin PET. However, there are numerous technical and economic challenges associated with rPET, including low supply of recycled resin, high recycling costs, and unpredictable material quality (OECD, 2018). Ultimately, these issues inhibit a large-scale substitution of virgin PET with rPET in plastic bottles.

PET is the most recycled plastic polymer in the U.S. and its use is associated with less environmental impacts than virgin PET. In 2018, 29.1 percent (1.3 million tonnes) of PET waste was recycled (US Environmental Protection Agency, 2017 [a]). Mechanical recycling is the predominant technology used globally. It includes sorting, washing, drying, and melting post-consumer PET, which is pushed through a metal grate into long strands, cut into pellets, and cooled in water (OECD, 2018). The environmental case for recycling is based on its benefits as a waste management strategy and substitute material. Recycling reduces the number of single-use products that end up in waste streams and the environment. Recycled material lessens demand for virgin PET and the fossil fuel inputs required for its production (Shen et al. 2010). In terms of climate

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[1] To be clear, this discussion does not attempt to address issues of bottled water quality, despite the concerns highlighted in section three. Improving water quality is an issue of regulation and water treatment standards, which are beyond the scope of this paper.

[2] https://usplasticspact.org/wp-content/uploads/2024/03/USPact_Roadmap-to-2025.pdf; https://environment.ec.europa.eu/strategy/plastics-strategy_en

benefits, a kilogram of rPET uses less than 10 percent of the total energy used to produce the same amount of virgin PET and emits about half of the emissions (OECD, 2018).

Despite these environmental benefits, technical issues affect the applicability of rPET in beverage containers. During recycling, PET's chemical and physical structures are degraded, and at least 7 percent virgin PET is added to ensure the integrity of the recycled material[3] (Brouwer et al., 2020). Beyond this, PET is only recyclable up to five times, so when used in single-use products the recycled material will eventually end up landfilled or in the environment (OECD, 2018). From a technical standpoint, rPET is thus best suited for applications with longer lifespans, such as textiles and construction materials, rather than single-use plastic bottles.

Furthermore, the current supply of rPET is not enough to satisfy growing demand for PET bottles. In the U.S., a widely quoted recycled content target for PET bottles is 25 percent by 2025. According to an industry research firm, if producers follow through on their commitments, this will require up to 3-times more recycled PET than is currently available. This is without factoring in demand for the material arising from other products (Taylor, 2023). Low supply of rPET in the U.S. is in part caused by lack of consumer participation in recycling programs. But the most problematic barrier for expanding the supply of rPET is underdeveloped recycling infrastructures due to chronic underinvestment.

Generally speaking, recycling in the U.S. is underfunded due to high recycling costs and competition from virgin plastics. Recycling is expensive, especially in terms of labor requirements, and automating technologies are not widely available. Recyclers often operate on a small scale, especially in comparison to virgin plastic producers. As a result of high costs and small operational scale, the price of recycled PET has recently exceeded the price of virgin PET by 3 percent in 2023, despite its inferior quality (Plastics News, 2023). This means that manufacturers tend to prefer the virgin polymer. With competition from virgin plastic producers, recyclers are often unprofitable and rely heavily on public subsidies. But recycling programs in the U.S. are chronically underfunded, since for decades the most economical option has been to ship plastics overseas as part of the global waste trade (OECD, 2018). Expanding supply for rPET requires significant structural changes in the market for recycled plastic and waste globally. These issues are well-established, but there has been limited progress in bolstering plastics recycling in the U.S.

To summarize, expanding the use of rPET requires concerted efforts to promote investment and increase recycling rates but, ultimately, technical issues related to polymer quality and recyclability limit the application of rPET in water bottles.

Bioplastic

There are many kinds of bioplastics (also referred to as 'biopolymers'). The most prevalent is polylactic acid (PLA), which is derived from bio-based feedstocks, is biodegradable, and promoted as a substitute material for plastic packaging, including PET bottles. The environmental benefits of PLA have been widely promoted (European Bioplastics, n.d.; Rosenboom et al., 2022; Rezvani Ghomi et al., 2021). But, in fact, their environmental impacts are not significantly better

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[3] Coca Cola's newest "100 percent recycled bottle" is likely no exception to this, since experts agree that at least 7 percent virgin PET must be added to assure the polymer's functionality (Brouwer et al., 2020).

than PET bottles. This is especially due to limitations for end-of-life management and land-use for bio-based feedstock cultivation. In addition, PLA production faces major economic barriers, including high production costs. These issues combined make PLA bottles an unlikely candidate to replace PET bottles.

In 2023, about 675,000 tonnes of PLA were produced, representing 31 percent of total bioplastic production globally. PLA is commonly made from corn, sugar, and agricultural and forest residues, including stems, husks, and leaves. In the first stage of its production, sugars derived from these organic materials are converted into lactic acid. Lactic acid is purified and, in the second stage, polymerized (Jamshidian et al., 2010). PLA is identical to fossil fuel-based plastics in appearance. They also possess many of the same technical advantages, including transparency, water resistance, and light weight. As such, most of PLA's applications are packaging for food and beverages. However, PLA-based packaging represents a very small share (less than 0.01 percent) of all fossil fuel and bio-based packaging materials.

Amid growing attention to PLA as a substitute for conventional plastics, industry, policymakers, and researchers speculate that demand for the material will grow significantly in coming years (*Bioplastics Market Development Update 2023*). Yet, there are economic obstacles which hinder its growth. PLA is more expensive than conventional plastics due to the high cost of cultivating bio-based feedstocks, building bio-refineries, and processing enzymes for the production of lactic acid (Wellenreuther et al., 2022). Strategies to decrease overall costs include building integrated biorefineries, where bio-based feedstocks are simultaneously processed into fuels, chemicals, and materials. However, integrated biorefineries have yet to be deployed at-scale since fossil fuel-based plastics continue to be the most competitive materials on the market (Chen et al., 2016).

Despite these economic challenges, PLA does have environmental benefits related to CO2 emissions. While fossil fuels are the primary energy source for PLA production, the bioplastic does not rely on fossil fuel-derived feedstocks. This results in PLA generating about half of the CO2 emissions as compared to PET (Papong et al., 2014; Gironi and Piemonte, 2011). These emissions could be further reduced by sourcing process energy from renewable energy resources. In addition, crops can sequester CO2 during their growth, so the production of PLA has potential to be completely free of fossil fuels as feedstock and energy source, and potentially carbon neutral or carbon negative.

However, PLA is associated with negative environmental impacts from the cultivation of feedstock crops. Crops are generally grown using fossil fuel-derived fertilizers, which release carcinogenic chemicals into the soil, water, and food supply. These chemicals are also linked to high eutrophication[4] and acidification[5] in aquatic environments, which damages animal life and natural vegetation. Additionally, crop feedstocks compete with food crops for agricultural space. According to a report by the World Bank, competition from crop feedstocks for land has contributed to past increases in world food prices. However, there is considerable uncertainty in

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[4] Eutrophication refers to an excess of nutrients in water, which diminish oxygen supplies and causes dense plant growth and death of animal life. This has compounding effects within and beyond aquatic ecosystems.

[5] Acidification refers to the release of acidic chemicals which can decrease the pH of water and soil, and damage vegetation, aquatic life, and soil fertility.

this regard, with estimates of biofuels' contribution to food price increases ranging from 15 percent to 75 percent (Chakrabortty, 2008; Sims et al., 2010; Chen et al., 2016). The use of agricultural waste and forest residues is a viable strategy to minimize competition with food crops, and decrease the environmental impacts of cultivation more generally (Sims et al., 2010; Chakrabortty, 2008; Chen et al., 2016). Nevertheless, Tabone et al. (2010) argues that the environmental advantages of bioplastics in terms of fossil fuel demand and CO2 emissions may lose significance when considering the breadth of these additional impacts (Chakrabortty, 2008; Sims et al., 2010; Chen et al., 2016; Tabone et al., 2010).

Downstream impacts from PLA are also significant. The main end-of-life pathways for PLA bottles include incineration, landfilling, and composting. The ability for PLA to biodegrade as the result of natural metabolic interactions differentiates it from conventional plastics. However, PLA only biodegrades in high temperatures and humidity, achieved primarily in industrial composting facilities. Industrial composting exists on a small scale in the U.S., and facilities are mostly concentrated in only a few states. Moreover, a third of U.S. industrial composters do not accept biodegradable packaging at all, due to contamination from look-a-like plastic packaging and concerns about the actual compostability of biodegradable plastics (Goldstein et al., 2023). Further, PLA is not recyclable with mechanical technologies, and instead must be reprocessed chemically (Aristi Capetillo et al., 2023). Like industrial composting, chemical recycling is not widely available in the U.S. Because of this, PLA often ends up landfilled or dumped into the environment, where it presents similar issues as PET.

End-of-life outcomes and upstream impacts in terms of land and fertilizer use suggest that PLA may not be as sustainable as prominent stakeholders suggest. Many of these stakeholders include large petrochemical and beverage companies which are also involved in PET bottle production. Bioplastic producers have also lobbied against plastic reduction policies. This demonstrates that the industry's primary aim is not to mitigate the environmental harm generated by their products (Eckert, 2021). The prospects for PLA as a substitute to PET water bottles are thus limited by these economic and environmental concerns.

Paperboard Cartons

Paperboard cartons are commonly used to package milk, juice, and other beverages (Kirwan, 2012). They are a strong contender for replacing PET bottles, despite their environmental impacts and the presence of low-density polyethylene plastic. This is because the infrastructures and markets for paperboard cartons are already well-established. In addition, their recycling is growing rapidly in the U.S. and demonstrates large benefits in terms of reducing overall impacts.

Over 9 million tonnes of paperboard packaging were used in the U.S. in 2022 (Valois, 2023). Paperboard is thicker, stronger, and more durable than standard paper, but similarly derived from wood fibers. Wood fibers are broken down into pulp, cleaned, and mixed with water and chemicals to form a paste, which is spread onto large screens and dried. This results in raw paperboard, from which two types of cartons are made: 'aseptic' cartons are coated with thin layers of low-density polyethylene plastic, to enhance durability and inhibit leakage, and aluminum foil, to extend shelf life. They are typically used for milk and other perishable liquids. 'Gable top' cartons are composed of paperboard with a layer of low-density polyethylene and are commonly used to package juice. Their exceptional lightweight and reasonable durability also make gable top cartons strong candidates for water packaging (Kirwan, 2012).

The thin layer of low-density polyethylene means that paperboard cartons do not facilitate a full transition away from plastics in beverage containers. On average, paperboard cartons use about 37 percent of the total plastics used in PET bottles (Agamuthu and Visvanathan, 2014). While this is a significant reduction, issues of chemical leaching and fossil fuel feedstock use remain. However, there are alternative materials which can be used to coat cartons. These include biodegradable and non-toxic natural materials such as cellulose[6], chitosan[7], and lignin[8] (Mujtaba et al., 2022). Bioplastics, including PLA, can also substitute low-density polyethylene for this application. According to Mujtaba et al. (2022), chitosan is the most favorable alternative due to its low environmental impacts and low cost. Al-Gharrawi et al. (2021) further point out that the use of natural and biodegradable materials makes paperboard recycling easier, since the materials are more readily separated from cartons than low-density polyethylene (Al-Gharrawi et al., 2021). Despite these benefits, alternative coating materials are not widely used in cartons, and progress on this front is modest.

Paperboard cartons have a range of environmental impacts. Paperboard production, like all paper products, relies on industrial wood harvests, and thus contributes to the felling of natural forests and establishment of monoculture tree farms (Kinsella et al., 2007). Its production is also energy intensive, and the paper industry ranks fourth globally in terms of industrial energy consumption, after steel, petrochemicals, and cement (Chiba et al., 2017). With most energy coming from fossil fuel resources, the production of paper products is associated with significant carbon emissions. In addition, the paper industry is the largest consumer of industrial process water in the U.S., where a single paper mill uses 4,000-12,000 gallons per ton of pulp produced (Kinsella et al., 2007). Paperboard is sanitized and bleached with a suite of chemicals, including hydrogen peroxide and sulfuric acid, which pollutes process water. Beyond this, paperboard cartons are typically single-use due to their design and material characteristics. This means that cartons often end up in landfills, where they occupy space and may leach embedded chemicals.

Many of these environmental impacts can be lessened with recycling, which demonstrates great potential in the U.S. (Todorova et al., 2015). Recycling gable top cartons involves shredding containers and feeding them into pulping machines, where they are broken down and low-density polyethylene is separated out using advanced technologies such as centrifuge, flotation, or hydrocyclones. The plastic and paper fibers are collected, and can be used to produce new cartons (if high quality), or lower value products such as construction materials or textile fibers (Breault, 2015; Agamuthu and Visvanathan, 2014). Over the past 15 years, the percent of U.S. households with access to carton recycling has grown from 37 percent to 62 percent, and this will likely increase, as cartons receive more attention as a potential alternative to plastic bottles (Carton Service, 2021)

Recycling reduces the environmental impacts of paperboard cartons by conserving natural resources and minimizing waste. When cartons are recycled, demand for virgin paperboard and

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[6] Cellulose is the main structural component in plant cell walls and the most abundant organic material on Earth

[7] Chitosan is an organic material derived from fungi, crustacean shells, and insects

[8] Lignin is a natural compound found the in the cell walls of plants, especially in wood and bark

low-density polyethylene declines. Recycling also greatly improves the efficiency of production, as common pulping processes require 2.2-4.4 tons of fresh trees to make one ton of virgin pulp, but only 1.4 tons of recycled paper are needed to produce the same amount (Kinsella et al., 2007). In addition, Kinsella et al. (2007) reports that, in comparison to 100 percent virgin paper, paper with 100 percent recycled content reduces total energy consumption by 44 percent, GHG emissions by 38 percent, particulate emissions by 41 percent, and solid waste generation by 49 percent. There is less research on the environmental benefits of increasing the recycled content of paperboard, specifically, but similar reductions in overall impact are likely. For these reasons, paperboard cartons are regarded as promising for the substitution of plastic bottles.

Glass

There is a strong historical precedent for glass, since the material was commonly used as beverage packaging before the emergence of PET bottles. Its prominence is attributed to aesthetic appeal and technical advantages: glass is transparent, impermeable to liquids and chemicals, and easy to sanitize. Yet, in recent decades, glass water bottles have been almost entirely replaced by PET. Today, the material represents only 2.3 percent of the global market for bottled water (International Bottled Water Association, n.d. [b]). Reversing these trends and expanding the use of glass to substitute PET bottles has generated some interest from researchers and policymakers, primarily because of the advantages that glass recycling offers. But overall, a shift towards glass containers is impeded by low recycling rates, environmental impacts, and high transportation costs.

Glass bottles are made by melting sand, soda ash, and limestone together, and molding the molten material into bottle form (Global Package, 2023). If designed with a resealable cap, the same glass bottle can be used multiple times, without any health risks. However, glass bottles are heavy and can break, which means they are usually not reused and frequently end up in waste streams. Recycling is the most advantageous waste management option for glass, since it can be recycled indefinitely, without any deterioration of its physical or chemical properties. The recycling process involves crushing glass containers into small pieces, which are cleaned and melted and can be used to manufacture new glass bottles with up to 95 percent recycled content (Glass Packaging Institute, n.d. [a]).

Virgin glass production requires large amounts of energy and raw materials, but recycling reduces this demand and its environmental impacts. The glass industry is one of the most energy-intensive industrial sectors in the U.S. In 2013, it accounted for 1 percent of the country's total industrial energy use (US Energy Information Administration, 2013). In 2019, the sector was responsible for over 2.9 million Mt CO2eq. emissions (US Environmental Protection Agency, 2022). Recycling glass reduces overall energy consumption by about 2-3 percent for every additional 10 percent of recycled material added, and GHG emissions are reduced by six tons for every ton of recycled material. Additionally, recycling lessens demand for sand and other material inputs and can actually improve the quality of glass products by limiting the occurrence of air bubbles and other distortions (Jacoby, 2019; Glass Packaging Institute, n.d. [b])

Despite this, only about 31 percent of glass entering U.S. waste streams is recycled (US Environmental Protection Agency, 2017 [b]). This pales in comparison to European countries, many of which recycle up to 90 percent of their glass (Mills, 2024). The main factor contributing to low recycling in the U.S. is the predominance of single-stream recycling systems, in which glass, paper, plastics, and metals are combined in a single bin for pickup and transport to material recovery facilities. During this process, glass can shatter, contaminating recycling streams and complicating the sorting process. As a result, recyclers face high costs, and mixed waste is often cheaper to send to landfills than process and recycle. In contrast, multi-stream recycling requires households to sort their waste by material-type, so that glass can be delivered directly to processers. This system is credited with high recycling rates across Europe but has garnered little traction in the U.S. due to additional collection costs and the general state of underinvestment in waste management (Jacoby, 2019). A further barrier for glass recycling in the U.S. is the geographical distance between waste management facilities, recyclers, and glass manufacturers. Glass is heavy, and high transportation costs discourage waste facilities from sending their recovered material to processers, who are similarly disincentivized to deliver recycled glass to far-off manufacturers (*2017 Glass Recycling Survey*).

Even with recycling, glass generates more environmental impacts than many other materials, including PET bottles. Although glass bottles with 100 percent recycled content have less impacts than PET bottles in terms of fossil fuel use, ecotoxicity, and photochemical oxidization, Brock and Williams (2019) find that 100 percent recycled glass bottles are worse than PET bottles when looking at acidification potential, lifecycle CO2 emissions, and human toxicity. In addition, glass is heavy, requiring significant energy during its transport, and is costly to produce. Ultimately, these issues make the material an unlikely alternative to PET bottles, despite its precedent as water packaging.

Aluminum

Aluminum is lightweight, durable, and more affordable than many other metals. After transportation applications, packaging is aluminum's largest application in the U.S. (*Industry Statistics: Facts at a Glance 2018,* 2020). Aluminum can be fabricated into reusable bottles, is 100 percent recyclable, and exhibits significantly improved environmental outcomes when recycled content is used. As aluminum production and recycling infrastructures are already well-established, the metal represents a favorable option as substitute for PET water bottles.

Aluminum production starts with mining for bauxite ore, which is refined into alumina, and smelted to produce pure aluminum. For beverage containers, the refined metal is rolled into sheets, cut into large discs, and entered into an impact extruder, which is a specialized machine that applies high pressure to punch discs into a mold (Cullen and Allwood, 2013). Aluminum is commonly molded into 330-milliliter (ml) cylindrical cans, but may also be crafted into differently shaped containers, such as bottles with slim necks and resealable caps. Cylindrical cans are more common due to technical issues; namely, the complex geometry of creating a thin bottleneck via impact extrusion, which can lead to deformities and higher rejection rates, and raise producer costs. According to Javidani et al. (2024), these issues can be addressed by using soft and highly formable aluminum alloys (Javidani et al., 2024). While bottles made from soft alloys are easier and more cost-effective to produce, they may result in more scratches and dents, and lower consumer appeal. Nevertheless, aluminum bottles are already available and marketed as reusable alternatives to single-use PET.

The environmental impact associated with aluminum production is the most significant challenge to expanding the metal's use as substitute for PET bottles. In 2022, the industry was responsible for 3 percent of the world's direct industrial emissions (International Energy Agency, n.d. [a]). More than 80 percent of emissions stem from upstream processes, and two-thirds are related to electricity (Saevarsdottir et al., 2020). Potential solutions include energy efficiency improvements and switching to renewable energy resources. But as the industry's energy intensity has declined by 15 percent over the last 15 years, many producers have exhausted potential efficiency gains. Significant progress can be made by switching from fossil fuels as the main energy source to renewables. But, according to the IEA, progress on this front is modest and the industry is not on track to achieve net zero emissions by 2050 (International Energy Agency, n.d. [a]).

The least technologically reliant and most timely strategy to reduce aluminum's impacts is through recycling. Aluminum, like glass, can be recycled continuously without any deterioration of the material's quality. Recycling involves collecting and cleaning post-consumer aluminum, shredding the metal into small pieces, and melting it in a furnace (Raabe et al., 2022). In the U.S., the recycling rate for aluminum containers was 50 percent in 2018, much higher than many other materials, including glass and plastic (US Environmental Protection Agency, 2017 [c]).

Major climate benefits can be achieved by recycling aluminum and increasing the proportion of recycled material in beverage containers. Since the industry's most energy intensive processes occur upstream during mining, refining, and smelting, recycling saves up to 95 percent of the energy and emissions as compared to making it from the original ore (Chen, 2013; Das et al., 2010). In addition, recycled aluminum lessens demand for bauxite ore and helps to reduce the number of aluminum products which are landfilled or incinerated (Capuzzi and Timelli, 2018). Despite these benefits, recycling exists on a much smaller scale than the production of primary aluminum. This is because primary production largely benefits from concentrated large-scale operations, whereas recyclers benefit from being geographically dispersed, to expand access to post-consumer aluminum and lessen transportation costs. But this results in smaller facilities and recycling capacities. According to Cullen and Allwood (2013), this means the supply of recovered aluminum lags well behind demand, thus preventing any significant shift away from primary use (Cullen and Allwood, 2013).

An additional benefit of aluminum is its reusability. Reusability differs from recycling as it refers to using a product multiple times, whereas recycling indicates that a product is broken down and made into something new. Aluminum is durable enough to be designed for multiple uses, which lessens demand for primary and recycled aluminum and energy and reduces the number of products ending up in waste streams. However, like paperboard cartons, reusable aluminum containers often include an added layer of low-density polyethylene to protect against acidic or corrosive substances and preserve the quality of its contents. This increases the human health risks of long-term aluminum bottle use but can be mitigated by substituting low-density polyethylene with natural coating options, as discussed previously. Nevertheless, Tamburini et al. (2021) find that the health risks of reusable aluminum bottles, with a lifespan of 2.5 years, are lower than those associated with single-use PET bottles (Tamburini et al., 2021).

On the other hand, there are social and cultural factors hindering the large-scale adoption of reusable containers. Since single-use plastic items emerged, the convenience of disposability has been embraced in the U.S. and globally. Reusable items must be carried around, cleaned, and stored, which can be seen as impractical and troublesome. Yet, sustainability efforts highlight reusability as an essential strategy for limiting environmental harm. Reuse thus needs to be re-normalized, through informational campaigns and the introduction of materials that facilitate long-term use, such as aluminum bottles.

Stainless Steel

Packaging applications represent a very small percentage of steel use globally, with only about 2 percent of all steel going to the production of cans, bottles, and other containers (*Steel Profile*). In recent years, however, stainless steel has gained popularity as a packaging material, with numerous companies have experienced success through marketing stylish and reusable stainless-steel bottles (*Reusable Water Bottle Market Size & Share Report, 2030*). Although the production of stainless steel generates significant environmental impacts, the material is extremely durable, facilitates reuse, and requires no internal coating of low-density polyethylene plastic, unlike aluminum. For these reasons, the material is a suitable substitute for PET bottles.

Stainless steel is a distinctive alloy composed of iron, carbon and at least 11 percent chromium to enhance the metal's aesthetic appeal and resistance to corrosion and chemicals (Deshwal and Panjagari, 2020). 66 percent of U.S. steel is produced via the electric arc furnace, in which iron ore, carbon, and scrap steel are melted in extremely high temperatures (1,600-1,800 degrees Celsius), and chromium is added to refine the mix's properties. Liquid stainless steel is then poured into molds or rolled into sheets, which thereafter can be manufactured into bottles. This production is well-established, exhibits low rejection rates, and produces highly durable material (*Steel Profile*; Björkman and Samuelsson, 2014).

Like aluminum and glass, stainless steel is 100 percent recyclable and can be reprocessed continuously without degrading its physical and chemical properties. The recycling process involves sorting and shredding, and entering scrap metal into the furnace alongside virgin material and other primary inputs (Björkman and Samuelsson, 2014). In the U.S., 74 percent of post-consumer steel was recycled in 2018, meaning more steel was recycled than paper, plastic, aluminum, and glass combined (*Steel Profile*; US Environmental Protection Agency, 2017 [d]).

The most significant environmental impact of steel production is its carbon intensity, but recycling is one of the main strategies for decarbonizing the industry. In 2022, steel production was responsible for about 8 percent of global energy demand and up to 7 percent of energy sector CO2 emissions. Many of these emissions could be avoided by switching the main energy source from coal, which currently accounts for 75 percent of the industry's source energy, to renewable sources. However, progress on this front is minimal and, with rising demand, especially from construction in developing countries, the IEA predicts that even in a sustainable development scenario which decreases the industry's emissions by 54 percent over the next 25 years, steel will produce 25-30 percent of direct global industrial carbon emissions by 2050 (International Energy Agency, 2020).

Recycled material used during production can reduce carbon emissions. *World Stainless* reports that, for one tonne of stainless steel with 30 percent recycled material, CO2 emissions are about 6.8 tCO2. Increasing the percent of recycled material to 85 percent reduces emissions by more than 69 percent, to 2.1 tCO2 per tonne (World Steel, 2023). Other research also reports notable reductions when the content of recycled material is increased (Björkman and Samuelsson, 2014; Kim et al., 2022; Johnson et al., 2008). However, increasing the percentage of recycled material is constrained globally, due to limited availability of steel scrap. Despite high recycling rates for packaging applications, steel scrap is in low supply because the metal's most important applications are often in use for decades (such as construction materials). This means that the quantity of recovered steel available for reprocessing is much less than overall demand for the metal, and large increases in the recycled content of beverage containers are unlikely.

Nevertheless, stainless-steel bottles can be reused, and environmental impacts including CO2 emissions can be lessened when bottles are in-use for long periods of time. Research on the potential for reusing stainless-steel bottles as a way to mitigate their environmental impacts is lacking, but as with the case of aluminum bottles, it is evident that reusability is a valuable way to enhance the environmental sustainability of packaging.

From this review, it is clear that there is no perfect alternative to PET bottles. All materials generate environmental impacts and present notable technical and economic challenges, which vary in intensity and relevance. The environmental impacts of alternative materials are the most important factors to consider when searching for more sustainable substitutes to PET bottles, but economic and technical challenges also influence the viability of their large-scale application. Glass, due to its heaviness and low recycling rates, is associated with too many environmental impacts and insufficient mitigation potential to be considered an appropriate alternative for PET bottles. rPET and PLA provide improved environmental outcomes, but economic and technical issues related to expanding supply present major challenges. Paperboard cartons and aluminum are also problematic with respect to environmental sustainability. Since they are commonly coated with polyethylene, they also wouldn't eliminate plastic from beverage packaging. Stainless steel eliminates this concern, but still generates environmental impacts across its lifecycle.

Nevertheless, I conclude that the most viable alternatives to PET bottles are paperboard cartons, aluminum, and stainless steel. Paperboard cartons are already widely used to package beverages, recycling rates are high and increasing, and growth in the use of natural wax to coat the material is promising. Aluminum and stainless steel are also widely available and recyclable, and their reusability has potential to significantly the environmental impacts of production. In the next section, I provide a more direct comparison of the environmental impacts of these materials with PET bottles to assess their relative sustainability.

5. COMPARING ENVIRONMENTAL IMPACTS OF ALTERNATIVES TO PET BOTTLES

Life cycle assessments (LCA) are typically employed to compare the environmental impacts of different products, including beverage containers. Studies measure CO2 emissions, resource depletion, acidification potential, and more, stemming from all stages of the product lifecycle, including raw material extraction, manufacturing, use, and disposal. While there are numerous LCA studies measuring the impacts of PET packaging, this review focuses on those which compare the PET bottles, paperboard cartons, aluminum bottles, and stainless-steel bottles.

Due to differences in methodologies and underlying data, LCA results are not directly comparable across studies. A major difference is their choice of functional unit (FU), which is the reference quantity that defines the function of the product under investigation. Its primary purpose is to provide a common basis for comparing the environmental impacts of different products (Tamburini et al., 2021). For beverage containers, FU is usually set to the amount of packaging needed for the consumption of some volume of liquid. For example, Franklin Associates (2009) measures the impacts of packaging required for 100,000 ounces of soft drink consumption. Results are often expressed in terms of functional unit but may be converted to per bottle impacts. The chosen capacity of the studied bottle thus influences how results are presented. For example, Amienyo et al. (2013) measures the impacts of packaging required for one liter of beverage, but the study's results are converted from this functional unit and reported in terms of a 330 ml cylindrical aluminum can (*Life Cycle Inventory of Three Single Serving Soft Drink Containers*, 2009; Amienyo et al., 2013).

Studies may also differ in terms of the system boundary, material inputs, and geographical scope. The system boundary of an LCA study refers to the stages of a product's lifecycle included in the analysis. Although LCAs generally measure the impact of a product from "cradle to grave", specific boundaries vary. For example, Simon et al. (2016) and Tamburini et al. (2021) include emissions associated with transportation, but transportation distances are different (Tamburini et al., 2021; Simon et al., 2016). In contrast, Brock and Williams (2019) don't include transportation at all (Brock and Williams, 2019). Results are also influenced by the selection of material inputs, including the total quantity of aluminum, plastic, paperboard, water, and energy. Finally, depending on geographical scope, the environmental impact data underlying material inputs may diverge. These differences make direct comparisons impossible. Instead, results from LCA studies are compared with respect to the relative performance of each material.

PET Bottles vs Paperboard Cartons

There are only a handful of studies which compare the environmental impacts of paperboard cartons and PET bottles. In these studies, the paperboard cartons generally demonstrate less environmental impacts than PET bottles. GHG emissions are assessed across all studies, and paperboard cartons are always attributed with the lowest impacts. In particular, Stramarkou Marina et al. (2021) find that the carbon footprint of a PET bottle is 2.6 times higher than a Tetra Pak carton, a common brand name. Simon et al. (2016) also find that cartons have relatively low greenhouse gas emissions when compared to ten other beverage packaging options, including PET bottles. The emissions associated with different end-of-life scenarios are estimated in this study, and cartons present the second-best environmental performance (after glass) when fully recycled (Stramarkou Marina et al., 2021; Simon et al., 2016).

Similarly, Persico (2019) reports that cartons generate less emissions than PET bottles. However, in comparison to the large divergence reported by other studies, they find only a 1 percent difference in total emissions. These relatively high emissions are due to the study's choice of an 'aseptic' carton (i.e. includes a layer of aluminum) as the reference container. Indeed, Persico

(2019) notes that carbon emissions are mostly attributed to the production of aluminum foil, as well as the transportation of cartons from manufacturers to distributors (Persico, 2019). This suggests that gable top cartons (which don't include aluminum) are more sustainable alternatives to PET bottles than aseptic cartons.

While all studies report GHG emissions, only three investigate additional environmental impacts, such as human toxicity, acidification, eutrophication, and photochemical ozone formation. For all categories, Brock and Williams (2019) find that cartons are less harmful than PET bottles. Stramarkou Marina et al. (2021) attain similar results, but report that cartons have a higher potential for eutrophication. According to the authors, high eutrophication is likely the result of chemicals used in paperboard production, which may end up in water and cause excessive oxygen-consuming reactions. Stramarkou Marina et al. (2021) also measure ecotoxic effects in aquatic environments and find that PET bottles contribute more to ecotoxicity than paperboard cartons (Stramarkou Marina et al., 2021; Brock and Williams, 2019).

A significant gap in LCA research on carton beverage containers is land use. Von Falkenstein et al. (2010) suggest that the occupation of land area by forestry systems is likely larger for cartons than for PET bottles, since paperboard is derived from wood fiber, while PET requires no biomass feedstock (von Falkenstein et al., 2010). Like PET bottles, cartons may also occupy significant landfill space since they are typically single-use and their recycling may be limited in regions without adequate infrastructures. However, relative environmental performance in terms of land use cannot be determined based on existing research.

There are several important findings that can be extrapolated from these studies. Most importantly, it is evident that gable top cartons are less environmentally harmful across their lifecycle than PET bottles and can thus be considered as a more sustainable single-use substitute. Nevertheless, how cartons are disposed of influences their overall environmental impacts. Without appropriate waste management infrastructures in place, cartons are associated with downstream impacts. It is also important to emphasize that LCA studies are subject to significant uncertainties, especially related to the accuracy of underlying data. As a result, the full extent of cartons' impacts, especially in terms of land use, is unclear, and while general conclusions in favor of cartons can be drawn, additional research is necessary.

PET Bottles vs Aluminum Bottles

There are several studies which compare the environmental impacts of PET bottles and aluminum bottles. Most look at the impacts of 330 ml cylindrical cans, which may require fewer material inputs than larger bottles, and are thus likely to have different environmental impacts. Because of this, LCA studies cannot be seen as a direct reflection of aluminum bottle impacts. Nevertheless, single-use aluminum containers are generally reported to have greater lifecycle impacts than PET bottles.

All studies compare the carbon footprint of aluminum and PET bottles, with results indicating that aluminum containers generate more CO2 emissions than plastic bottles across their lifecycle. The largest difference in GHG emissions is reported by Tamburini et al. (2021), who finds that the global warming potential of a 750 ml aluminum bottle is 88 times larger than a 500 ml PET bottle. According to Franklin Associates (2009), cylindrical aluminum cans emit twice the amount of overall emissions as a PET bottle. Several studies, including Tamburini et al. (2021), Simon et al. (2016), Ghenai (2012), and Franklin Associates (2009) attribute the large carbon footprint to the production of primary aluminum from bauxite ore. Primary aluminum, however, only needs to be used in small amounts, since recycled aluminum demonstrates the same physical qualities as its primary counterpart. Measuring the relative impact of containers made primarily from secondary aluminum, Brock and Williams (2019) and Simon et al. (2016) find that emissions are significantly reduced, and less than the emissions stemming from PET bottles.

Comparative impacts across other categories are more mixed. For example, Brock and Williams (2019) find that cylindrical cans made from primary aluminum have more impacts across all categories except for ozone depletion. Amienyo (2013), on the other hand, finds that aluminum is less harmful in terms of abiotic depletion potential, eutrophication, and ozone depletion, while Saleh (2016) reports that aluminum cans are less toxic for human health. These differences may be explained by the respective system boundaries of each study. Brock and Williams (2019) include the impacts of beverage manufacture, and impacts stemming from the secondary packaging used to distribute bottles. End-of-life pathways also vary, and studies which allocate higher recycled content and recycling rates to aluminum arrive at more favorable results for the metal. For example, although Brock and Williams (2019) find that cans made from primary aluminum generate more impacts, they also find that cans made from 100 percent recycled aluminum are less harmful across all but one impact category than their virgin counterpart and PET bottles.

Results generally indicate that beverage containers made from primary aluminum are not sustainable alternatives to plastic bottles, in terms of their global warming potential and other impacts. Recycling, however, greatly reduces these impacts, and depending on the amount of recycled content may improve aluminum's performance in comparison to PET. In addition to recycling, reuse is a potential way to lessen the impacts of aluminum containers. While the benefits of aluminum recycling are well-documented, only a couple of studies discuss the reusability of aluminum containers. Tamburini et al. (2021) suggests that the average lifespan for an aluminum bottle can be upwards of 2.5 years, finding that when reused daily for this period, aluminum bottles perform better than PET across all environmental impact categories, with the largest reduction being their global warming potential.

Circular economy literatures and other plastic policy dialogues emphasize recycling *and* reuse as critical and complementary strategies for mitigating the environmental harm of packaging. Although there is minimal documentation of the potential for reuse to lessen aluminum's impacts, circular economy research asserts that the environmental benefits are intuitive: there is less demand for new products when items are reused, which lessens demand for raw materials and the activities associated with their extraction; reuse also reduces the number of beverage containers that are thrown away, which minimizes their downstream impacts, whether landfilled, incinerated, polluted, or recycled. These factors, in addition to the results from Tamburini et al. (2021), indicate that reusable aluminum bottles may be a sustainable alternative to single-use plastic bottles.

However, aluminum bottles can only be considered sustainable alternatives if they are reused enough times so that overall impacts are certainly less than PET bottles. Pathwater, a manufacturer of reusable aluminum bottles, refers to this as the “break even” point, or the minimum number of times an aluminum bottle must be reused for impacts to be equal. Break-even points for each impact category are determined by dividing the impact value of an aluminum bottle by the impact value of a PET bottle. For instance, Pathwater reports that the production of an aluminum bottle generates 0.37 kg CO2eq, while a PET bottle emits 0.16 kg CO2eq. The emissions for aluminum bottle production are more than two times greater than PET bottles, which implies that the production emissions of aluminum bottles “break even” after three uses (Pathwater, 2019). Pathwater focuses solely on upstream emissions, but their methodology for calculating break-even points is applied to determine break-even points across all relevant impact categories.

Break-even points may be calculated using results from any comparative LCA study. For this study, results from Tamburini et al. (2021) are used to calculate break even points across eleven impact categories. Tamburini et al. (2021) results are applied because impacts are reported for a reusable aluminum bottle, rather than a single-use cylindrical can. The material inputs include 107.1 grams of aluminum, which far exceeds the aluminum required to produce a cylindrical can and implies more durability and higher reusability.

Table 1 reports the impacts generated from the production of one PET bottle and one aluminum bottle for eleven environmental impact categories. For instance, the climate change impact generated from a PET bottle is about 0.1 kgCO2eq. and about 11.9 kgCO2eq. for an aluminum bottle. For this impact to break even, the aluminum bottle must be used 89 times $(11.921/0.134 = 89)$. Across all categories, eutrophication demonstrates the largest impact difference between the two bottles (with a break-even point of 482). Thus, for impacts to break even across all categories, an aluminum bottle must be reused at least 482 times.

Table 1. Number of uses for impacts from PET bottle and aluminum bottle to ‘break even’

Impact Category	**1 PET bottle**	**1 aluminum bottle**	**Number of uses to reach break even point**
Climate change (kgCO2eq)	0.1	11.9	89
Eutrophication (kgPO4eq.)	2.28E-05	1.10E-02	482
Ozone Layer Depletion (kgCFC-11b)	9.82E-06	5.19E-07	0.1
Acidification (kgSO2eq.)	5.20E-04	5.40E-02	104
Photochemical oxidant (kgNMVOCa)	3.10E-04	2.79E-02	90
Fossil depletion (kgoileq.)	0.1	3.2	59
Water depletion (liters)	7	477	68
Human toxicity (kg1,4-DBc)	0.1	5.5	110
Ecotoxicity (kg1,4-DB)	2.15E-03	0.3	124
Land occupation (m2)	2.01E-03	0.2	80
Particulate matter formation (kgPM10eq.)	1.70E-04	1.79E-02	105
Source: *adapted from Tamburini et al. (2021)*			

In the U.S., people consume 397 milliliters of bottled water per day on average (author’s calculations). Assuming no change in daily consumption, this means that an aluminum bottle that is reused 482 times would be in-use for 91 days, or 2.5 years. This is only slightly more than the 2.5 year average lifespan of an aluminum bottle indicated by Tamburini et al. (2021). It is therefore evident that the impacts generated from aluminum bottles break even with PET bottles within acceptable range of the product's lifespan.

Aluminum Bottles vs Stainless-Steel Bottles

Despite the growing popularity of reusable stainless-steel water bottles, no studies were found comparing their environmental impacts to PET bottles. Therefore, the research to date is not sufficient to perform a careful evaluation. To assess the environmental impacts of stainless-steel bottles and determine a reuse rate, this study instead compares their impacts with aluminum bottles, for which a break-even point has already been established.

Research comparing stainless-steel and aluminum bottles is also minimal, and only one non-peer reviewed study comparing their impacts was found. The State of Oregon Department of Environmental Quality released a report comparing the impacts of various water consumption systems, including the distribution of tap water to state residents, and its consumption via three types of reusable bottles (aluminum, steel, and glass). The study assesses impacts associated with water processing, production of packaging containers, filling, transport, and end-of-life waste management. Results indicate that for all ten categories, including energy use, global warming potential, and waste volume produced, stainless-steel bottles, which are used daily for a period of one year, perform better than aluminum bottles with the same reuse frequency and duration. Estimates for the average carbon emissions of steel and aluminum processing (excluding mining, manufacturing, and transportation) provided by the IEA confirm that steel is better than aluminum in terms of global warming potential, generating only 22 percent of the CO2 emissions (International Energy Agency, n.d. [b]). These results indicate that reusable stainless-steel bottles may need to be used fewer times than aluminum bottles to reach a break-even point with PET bottles. However, this result must remain provisional at present, due to the lack of careful research on the question.

In particular, aluminum bottles may present better outcomes than stainless-steel bottles depending on transportation distances and the potential for increasing recycled content. Stainless steel is up to three-times heavier than aluminum, which means that more emissions are generated when transporting of the same volume of material. Stainless steel is also less malleable, so more energy is needed to extrude the metal during manufacturing (Industrial Metal Service, 2024). And with a larger share of emissions coming from manufacturing, recycled steel has less energy saving potential than recycled aluminum (Raabe et al., 2022). Recycling rates are much lower for aluminum than for stainless steel, which means there is more room for improvement, especially since aluminum products on average have a lower lifetime expectancy. On the other hand, the risk of chemical leaching from stainless-steel bottles is minimal since the metal does not need to be coated with low-density polyethylene (Industrial Metal Service, 2024). Overall, research suggests that stainless-steel bottles have better environmental outcomes, but as described additional documentation is lacking.

It is thus difficult to compare stainless-steel bottles to aluminum bottles, much less determine the number of reuses necessary for the impacts of stainless-steel bottles to break even with PET bottles. For these reasons, lifecycle impacts generated by stainless-steel bottles are assumed to have the same break-even point as aluminum bottles. That is, this study assumes that impacts from stainless-steel bottles break-even with PET bottles after 482 uses.

6. MODELING ALTERNATIVE SCENARIOS FOR PHASIING OUT PET BOTTLES

Goal and scope

The aim of this section is to estimate the costs of substituting single-use PET bottles with a mix of single-use cartons and reusable aluminum bottles over the period 2023-2050. Looking specifically at the U.S., three scenarios are modeled. The first estimates business-as-usual demand for PET bottles and total production costs to 2050. The 50 percent reduction scenario estimates costs of reducing and substituting plastic bottles to 50 percent of business-as-usual projections to 2050, and the 90 percent reduction scenario reduces plastic bottle use by 90 percent to 2050.

Materials and methods

5.2.1 Per unit container costs

Costs of production are calculated separately for each beverage container. Starting with the 500 ml PET bottle, Table 2 reports the required material inputs and their market prices. This includes 16.8 grams of virgin PET resin ($2,049/tonne), 2.3 grams of rPET ($2,113/tonne), 2.02 grams of polypropylene plastic resin ($1,536/tonne, for the cap and label), and 0.012 kWh of electricity ($0.17/kWh). The average recycled content of PET bottles is assumed to be 12 percent. Estimates for average recycled content vary, but it is generally reported that between 6 percent and 18 percent of a bottles' weight is comprised of recycled material (Souder et al., 2020). Additional inputs are required upstream to produce PET and polypropylene resins; however, these costs are assumed to be embedded in the polymers' market prices.

Table 2. Material inputs and market prices for 500 ml PET bottle

Material	**Input quantity**	**Market price**	
Virgin PET	16.8 grams[1]	$2,049/tonne[3]	
rPET	2.3 grams[1]	$ 2,113/tonne[3]	
Polypropylene	2.015 grams[2]	$1,536/tonne[3]	
Electricity	0.012 kWh[1]	$0.17/kWh[4]	
[1] *Tamburini et al. (2021);* [2] *Calrecycle (2011);* [3] *Plastics News;* [4] *U.S. Bureau of Labor Statistics*			

In Table 3, the total cost of production for a PET bottle is shown. Each material input costs less than $0.04. In total, one 500 ml PET bottle costs $0.0514 to produce.

Table 3. Production costs for 500 ml PET bottle

Inputs	**Quantity**	**Price/bottle**	
PET resin	16.8 grams	$ 0.03	
rPET resin	2.3 grams	$ 0.005	
Polypropylene resin	2.015 grams	$ 0.003	
Electricity	0.012 kWh	$ 0.002	
Labor	7% total costs[1]	$ 0.004	
Other	7% total costs[1]	$ 0.004	
Cost/bottle		**$ 0.0514**	

Source: *[1] Cost Competitiveness of PET, Aluminium, and Glass Beverage Containers (2022)*

The main inputs to produce an aluminum bottle include primary aluminum, secondary aluminum, polypropylene resin (for the cap), low-density polyethylene (for coating), electricity and labor. Input quantities are extrapolated primarily from Tamburini et al. (2021), who assess the impacts associated with a 750 ml aluminum bottle. Since the other containers in this study are 500 ml, material requirements reported by Tamburini et al. (2021) are proportionally adjusted to reflect a 500 ml capacity bottle. Electricity requirements are assumed to remain the same.

Table 4 reports that one 500 ml aluminum bottle requires 31.4 grams of primary aluminum ($2,270/tonne), 47.1 grams of recycled (secondary) aluminum ($1,505/tonne), 4.7 grams of polypropylene ($1,536/tonne), 4.7 grams of low-density polyethylene ($1,635/tonne), and 2.3 kWh of electricity ($0.17/kWh). The quantity of recycled aluminum allocated is based on the average recycled content of an aluminum can in the U.S., which is 66 percent (Raad et al. 2022).

Table 4. Material inputs and market prices for 500 ml aluminum bottle

Input	**Quantity**	**Market Price (2023 average)**
Primary aluminum	31.4 grams[1]	$2,270/tonne[2]
Secondary aluminum	47.1 grams[1]	$1,505/tonne[2]
Low density polyethylene	4.7 grams[1]	$1,635/tonne[3]
Polypropylene	4.7 grams[1]	$1,536/tonne[3]
Electricity	2.3 kWh[1]	$0.17/kWh[4]

Source: [1] Tamburini et al. (2021); [2] Mineral Commodity Summaries 2024; [3] Plastics News; [4] U.S. Bureau of Labor Statistics

Table 5 reports the production costs for a single aluminum bottle. The costliest input is electricity, at $0.38, followed by labor and 'other', which combined account for 17 percent of total costs. Prices of other inputs range between $0.01 (for low-density polyethylene and polypropylene) and $0.07 (for primary and secondary aluminum). As shown in Table 5, a 500 ml aluminum bottle costs $0.65 to produce.

Table 5. Production costs for 500 ml aluminum bottle

Input	Quantity	Price/bottle
Primary aluminum	31.4 grams	$0.07
Secondary aluminum	47.1 grams	$0.07
Low density polyethylene	4.7 grams	$0.01
Polypropylene	4.7 grams	$0.01
Electricity	2.3 kWh	$0.38
Labor + other	17% total costs[1]	$0.11
Cost/bottle		**$0.65**
Source: [1] Cost Competitiveness of PET, Aluminium, and Glass Beverage Containers (2022)		

High-quality stainless steel (typically 304-grade) is used to manufacture the body and cap of a stainless-steel bottle. The only other required material is a silicone ring, which is fitted into the steel cap to prevent leakage. A 500 ml stainless steel bottle reportedly weighs 200 grams (*Single Wall Stainless Steel Water Bottle with Lid*, n.d.). It's unclear what percentage of total weight is attributed to the silicone ring, but considering that silicone is exceptionally lightweight, this study attributes 1 percent of the bottle's weight to the silicone component. That is, a stainless-steel bottle requires 198 grams of stainless steel and 2 grams of silicone.

Estimates for the average recycled content in stainless steel bottles are unavailable or non-existent; however, several popular bottle companies, including Stanley and Klean Kanteen, report that their bottles include 50 percent and 90 percent recycled steel, respectively (https://www.stanley1913.com/pages/sustainability; https://www.kleankanteen.com/pages/recycled-steel). To reflect the use of recycled content, this study assumes that bottles are made with 50 percent post-consumer stainless steel. No sources were found reporting average electricity, labor, or operating costs. Since manufacturing stainless steel is widely reported to be more energy intensive than aluminum manufacturing, it is assumed that total electricity requirements for stainless steel bottles are double those for aluminum. In terms of additional labor and operating costs, these are assumed to mirror aluminum bottles at 17 percent of total costs, combined.

Tables 6 reports the material inputs and market prices for producing a single 500 ml stainless-steel bottle. Specifically, 99 grams of primary stainless steel ($1,987/tonne), 99 grams of secondary stainless steel ($1,050/tonne), 2 grams of silicone ($8,547/tonne), and 4.6 kWh of electricity ($0.17/kWh) are required.

Table 6. Material inputs and market prices for 500 ml stainless steel bottle

Material	**Input quantity**	**Market price**
Stainless steel	99 grams[1]	$1,987/tonne[2]
Recycled stainless steel	99 grams[1]	$1,050/tonne[3]
Silicone	2 grams[5]	$8,547/tonne[2]
Electricity	4.6 kWh[5]	$0.17/kWh[4]

Source: [1] Ethika Inc; [2] Intratec Stainless Steel Prices; [3] Scrapmonster.com; [4] U.S. Bureau of Labor Statistics; [5] Author's assumptions

In Table 7, the costs of each input and the total cost of producing a 500 ml stainless-steel bottle are shown. Like aluminum, the costliest input is electricity ($0.77). The costs of additional inputs are $0.22 (labor and 'other'), $0.20 (stainless steel), $0.10 (recycled stainless steel), and $0.02 (silicone). Total costs of production come to $1.313 per bottle.

Table 7. Production costs for 500 ml stainless steel bottle

Inputs	**Quantity**	**Price/bottle**
Stainless steel	99 grams	$0.20
Recycled stainless steel	99 grams	$0.10
Silicone	2 grams	$0.02
Electricity	4.6 kWh	$0.77
Labor and 'other'	17% total costs[1]	$0.22
Cost/bottle		**$1.313**

Source: [1] Cost Competitiveness of PET, Aluminium, and Glass Beverage Containers (2022)

As shown in Table 8, and according to Brock and Williams (2019) and Agamuthu and Visvanathan (2014), a 500 ml paperboard carton requires 26.25 grams of paperboard ($1,809/tonne), 7 grams low of low-density polyethylene ($1,635/tonne), 1.75 grams of polypropylene ($1,536), and 0.69 kWh electricity ($0.17/kWh). Given the high recyclability of cartons, it is likely that recycled paperboard assumes some percentage of total paperboard content. Unfortunately, data for average amounts are unavailable or non-existent, so 0 percent was assumed.

Table 8. Material inputs and market prices for 500 ml paperboard carton

Material inputs and market prices	**Quantity**	**Market Price (2023 average)**
Paperboard	26.25 grams[1]	$1,809/tonne[4]
Low density polyethylene	7 grams[1]	$1,635/tonne[3]
Polypropylene	1.75 grams[2]	$1,536/tonne[3]
Electricity	0.69 kWh[1]	$0.17/kWh[5]

Source: [1] Brock and Williams (2019); [2] Agamuthu and Visvanathan (2014); [3] Plastics News; [4] EUWID Paper and Pulp; [5] U.S. Bureau of Labor Statistics

Sources reporting additional labor and operating costs for paperboard carton production were also unavailable. These costs are therefore assumed to account for 14 percent of total costs, mirroring PET bottles. In Table 9, it is reported that a single 500 ml carton costs about $0.19 to produce. This includes $0.12 for electricity, $0.03 for paperboard, $0.01 for low-density polyethylene, labor, and other, and $0.003 for polypropylene.

Table 9. Production costs for 500 ml paperboard carton

Inputs	**Quantity**	**Price/Bottle**
Paperboard	26.25 grams	$0.03
Low density polyethylene	7 grams	$0.01
Polypropylene	1.75 grams	$0.003
Electricity	0.69 kWh	$0.12
Labor	*7% total costs*[1]	$0.01
Other	*7% total costs*[1]	$0.01
Cost/bottle		**$0.19**
Source: [1]*Author's assumptions*		

The results of this cost analysis (summarized in Table 10) validate the widely held assumption that PET bottles are cheaper to produce per unit than many alternatives, including paperboard cartons, aluminum bottles, and stainless-steel bottles. Specifically, the total cost of producing one 500 ml PET bottle is about 25 percent of the cost of producing a carton of the same size; 7 percent of the cost of an aluminum bottle; and 4 percent of the cost of a stainless-steel bottle. High per unit costs for aluminum and stainless-steel bottles are largely attributed to electricity and the large quantity of high-value metal required to make a sturdy bottle. Metal costs could be reduced if a greater share of recycled material is used. Indeed, manufacturers of aluminum and stainless-steel containers are inclined to shift to secondary material when available, since market prices are typically much lower than those for its virgin counterpart. By contrast, PET bottles are inexpensive to produce given their low input requirements, but since recycled PET is more expensive than virgin PET, producers are not inclined to shift their production to more recycled material. Cartons are a middle-ground option, requiring less overall material inputs as compared to aluminum and stainless steel, but exhibit higher costs than PET bottles due mostly to more electricity consumption. The per unit bottle costs presented here are used to calculate total costs of production, under policy scenarios discussed in the following section.

Table 10. Cost of 500 ml PET bottle, paperboard carton, aluminum bottle, and stainless-steel bottle

	Cost/500 ml bottle
PET	$0.05
Paperboard carton	$0.19
Aluminum	$0.65
Stainless steel	$1.27
Source: Author's calculations	

Policy Scenarios

The business-as-usual scenario projects demand for plastic bottled water from 2023-2050 assuming no shift to substitute materials. The average annual growth of plastic bottles is calculated based on historical bottled water consumption data from the International Bottled Water Association for 1992-2020. The data reports yearly consumption in gallons for all plastic bottle types, including retail gallon containers and 500 ml bottles. According to the Beverage Marketing Corporation, 71.2 percent of bottled water in 2022 was consumed from 500 ml PET bottles (Beverage Marketing Corporation, 2023). This ratio is assumed to remain constant over time and is applied yearly to calculate the total volume of water consumed from 500 ml PET bottles, specifically. Yearly demand for PET bottles is calculated using equation 1.

Equation 1. PET bottle demand

$$PET_t = \left(\frac{W_t}{V_{PET}}\right) \times g_s$$

$W_t = annual\ water\ consumption\ (in\ milliliters)$
$V_{PET} = volume\ capacity\ of\ PET\ bottle\ (500\ ml)$
$g_s = plastic\ water\ bottle\ annual\ growth\ rate\ (6.38\ percent)$

Two plastic bottle reduction scenarios are considered. It is important to note that each scenario models a reduction in demand for plastic bottles, *not* a reduction in demand for packaged water. Indeed, reducing demand for packaged water could lead to a decline in demand for PET bottles, and could thus be considered as a scenario to reduce PET bottle consumption. As explained earlier, however, it is unlikely that demand for packaged water will decrease significantly, given the widespread popularity and convenience of carrying water in portable containers. Thus, this study only considers scenarios in which the total volume demand for packaged water continues to grow at a rate of about 6.4 percent per year, but plastic bottles decline and are substituted with alternatives.

As shown in Table 11, the first reduction scenario reduces plastic bottle use to 50 percent of business-as-usual projections to 2050, meaning plastic bottles grow at a rate of 3.3 percent per year. In the second scenario, plastic bottle use declines to 90 percent of business-as-usual projections, which implies a yearly reduction of 2.4 percent.

Table 11. Annual growth rate for three scenarios of plastic water bottle demand from 2023 to 2050

Scenarios	**% Annual Change**
Business-as-usual	6.38%
50 percent reduction	3.32%
90 percent reduction	-2.45%
Source : *Author's calculations*	

For each scenario, four different substitution scenarios are modelled. In the first, the decline in plastic bottle consumption is offset by an increase in 'combined alternatives'. That is, one-third of the water that would have been consumed from PET bottles is now consumed from paperboard cartons, one-third is consumed from reusable aluminum bottles, and one-third is consumed from reusable stainless-steel bottles. Aluminum and stainless-steel bottles are assumed to be reused 500 times, which means that over their entire lifespans a single bottle carries 250,000 ml of water. Equations 2, 3, and 4 calculate yearly demand for cartons, aluminum, and stainless-steel bottles, respectively.

Equation 2. Carton demand

$$CAR_t = \frac{(W_t - W_{PET}) \times 33.3\, percent}{V_{CAR}}$$

$W_{PET} = volume\ of\ water\ consumed\ via\ PET\ bottles\ (in\ milliliters)$
$V_{CAR} = volume\ capacity\ of\ single - use\ carton\ (500\ ml)$

Equation 3. Aluminum bottle demand

$$A_t = \frac{(W_t - W_{PET}) \times 33.3\, percent}{L}$$

$W_{PET} = volume\ of\ water\ consumed\ via\ PET\ bottles\ (in\ milliliters)$
$L = \ lifetime\ volume\ capacity\ of\ reusable\ aluminum\ bottle\ (250{,}000\ ml)$

Equation 4. Stainless steel bottle demand

$$S_t = \frac{(W_t - W_{PET}) \times 33.3\, percent}{L}$$

$W_{PET} = volume\ of\ water\ consumed\ via\ PET\ bottles\ (in\ milliliters)$
$L = \ lifetime\ volume\ capacity\ of\ reusable\ stainless\ steel\ bottle\ (250{,}000\ ml)$

In the 'carton substitution' scenario, residual demand for packaged water is assumed to be fulfilled by paperboard cartons. In the 'aluminum substitution' scenario, residual demand is fulfilled entirely by aluminum bottles, and in the 'stainless steel substitution' scenario demand is fulfilled solely by stainless-steel bottles. Equations 2-4 are used to calculate demand for these additional substitution scenarios, but the 33.3 percent proportion of total residual demand for packaged water is increased to 100 percent in each case.

For each policy scenario, total costs of production are calculated using equations 4-6. Per unit production costs are assumed to remain constant over time.

Equation 5. PET production costs

$$C_{PET} = PET_t \times P_{PET}$$

$P_{PET} = unit\ cost\ of\ PET\ bottle$ (\$0.05)

Equation 6. Carton production costs

$$C_{CAR} = CAR_t \times P_{CAR}$$

$P_{CAR} = unit\ cost\ of\ carton$ (\$0.19)

Equation 7. Cost of aluminum bottle production

$$C_A = A_t \times P_A$$

$P_A = unit\ cost\ of\ aluminum\ bottle$ (\$0.65)

Equation 8. Cost of stainless-steel bottle production

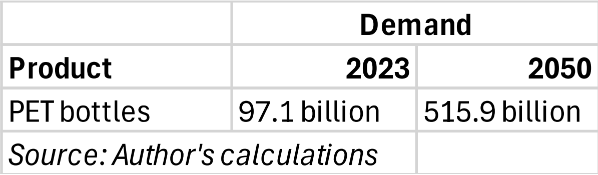
$$C_S = S_t \times P_S$$

$P_S = unit\ cost\ of\ stainless\ steel\ bottle$ (\$1.31)

7. SUMMARY RESULTS FROM MODELING EXERCISES

From 2023-2050, demand for packaged water in the U.S. is projected to increase at a rate of about 6.4 percent yearly, from 12.8 to 68.1 billion gallons. In the business-as-usual scenario, single-use PET bottles are the only option for packaged water, so demand for the product grows at the same rate as demand for packaged water. As shown in Table 12, plastic bottle demand increases from 97 billion bottles per year in 2023 to 517 billion bottles in 2050. In total, approximately 7.1 trillion PET bottles are used during the 28-year period. At 5 cents per bottle, the yearly average cost of production is about \$13 billion. Over the entire period, the total cost of producing PET bottles is \$357.8 billion.

Table 12. Quantity demand for PET bottles in 2023 and 2050 under business-as-usual scenario



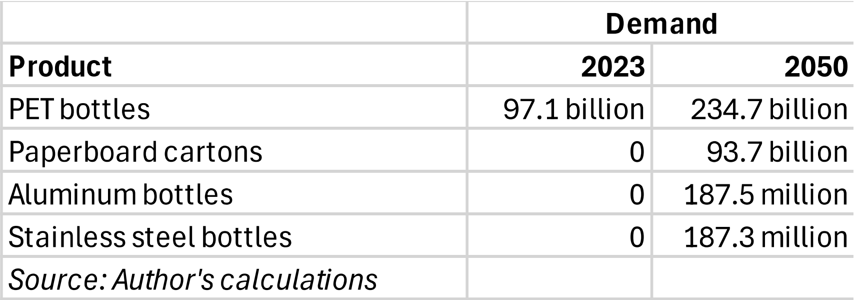
	Demand	
Product	**2023**	**2050**
PET bottles	97.1 billion	515.9 billion
Source: Author's calculations		

Most of these single-use PET bottles will be thrown away after a single-use. That is, under the business-as-usual scenario, almost 7.1 trillion bottles would enter U.S. waste streams over the next three decades. Waste management infrastructures are insufficient for properly managing the amount of plastic waste generated today. This will be true even after allowing for significant investments in upgrading waste management infrastructures. This means that a huge amount of plastic bottle waste will accumulate in landfills and pollute the environment, generating environmental impacts more severe than those that have already been experienced within the U.S. In addition to this, the relatively low rate of recycling—29.1 percent of PET waste as of 2018—implies that the material value embedded in plastic bottles, which exceeds $350 billion, will be lost over the period, instead of reutilized or reintegrated into other products. This underscores the large environmental and economic costs of business-as-usual plastic bottle use.

A relative decline in PET bottle use to 2050 is modeled in the 50 percent reduction scenario. This means that the total number of PET bottles used over the period continues to grow, but more slowly than in the business-as-usual scenario. As reported in Table 13, demand increases at a yearly rate of about 3.3 percent, to 234.7 trillion bottles in 2050, equal to less than half of business-as-usual PET bottle demand. Total plastic bottle consumption over the period declines from 7.1 trillion to 4.4 trillion. Average yearly production costs for plastic bottles decrease from $13 billion to $8 billion, and costs for their production over the period are reduced to $224.2 billion.

Although the use of PET bottles as water packaging declines in this scenario, demand for packaged water continues to grow at a rate of 6.4 percent, as in the business-as-usual scenario. The residual demand for packaged water is fulfilled by an equal proportion of single-use paperboard cartons, reusable aluminum bottles, and reusable stainless-steel bottles. Table 13 also reports demand for these alternatives. By 2050, 93.7 billion paperboard cartons, 187.5 million aluminum bottles, and 187.3 million stainless-steel bottles are required yearly. Note that the total quantities demanded for aluminum bottles and stainless-steel bottles are about equal. This is because the metal containers are modeled to be of equal capacity and assumed to have the same lifespan (i.e. each bottle carries 250,000 ml over their lifespans). Naturally, if the capacity or lifespan were to increase for aluminum or stainless-steel bottles, total demand for each container in 2050 would decrease.

Table 13. Quantity demand for PET bottles, cartons, aluminum bottles, and stainless-steel bottles in 2023 and 2050 under 50 percent reduction scenario



	Demand	
Product	**2023**	**2050**
PET bottles	97.1 billion	234.7 billion
Paperboard cartons	0	93.7 billion
Aluminum bottles	0	187.5 million
Stainless steel bottles	0	187.3 million
Source: Author's calculations		

Table 14 reports total demand for each container from 2023-2050, average yearly production costs, and total production costs. Specifically, transitioning to this mix of PET bottles, paperboard cartons, and reusable aluminum and stainless-steel bottles costs $14.2 billion per year on average. The costliest containers are PET bottles ($8 billion per year), followed by paperboard cartons ($6.1 billion per year), stainless-steel bottles ($84.4 million per year), and aluminum bottles ($41.8 million per year). Total costs over the period come to $398.9 billion, which is about 11 percent more than total costs in the business-as-usual scenario.

Table 14. Quantity demand and total costs for 28-year period (2023-2050) for PET bottles, paperboard cartons, aluminum, and stainless-steel bottles under 50 percent reduction scenario

Product	**Demand**	**Average yearly production costs**	**Total production costs**
PET bottles	4.4 trillion	$8 billion	$224.2 billion
Paperboard cartons	901 billion	$6.1 billion	$171.2 billion
Aluminum bottles	1.8 billion	$41.8 million	$1.2 billion
Stainless steel bottles	1.8 billion	$84.4 million	$2.4 billion
Total	**5.3 trillion**	**$14.2 billion**	**$398.9 billion**
Source: Author's calculations			

Notably, the quantity demanded of aluminum and stainless-steel bottles and the costs of their production are less than for PET bottles and paperboard cartons. This is attributed to the reusability of the aluminum and stainless-steel containers. Under the assumption that each metal bottle is reused 500 times, a 500 ml bottle will carry 250,000 ml of water over its entire lifetime, whereas the single-use containers only carry 500 ml of water. Thus, while the per production unit costs of aluminum and stainless-steel bottles are much higher than the costs of PET bottles and paperboard cartons, their long lifespans mean that the quantity of metal bottles needed to fulfill demand for packaged water, and thus total costs for their production, are less than single-use alternatives.

Quantity demand and production costs are also calculated under the assumption that residual demand for packaged water is satisfied completely by each substitute container. Table 15 reports the quantity demand for each case. For instance, when PET bottle use declines by 50 percent of business-as-usual to 2050, and residual demand is fulfilled entirely by paperboard cartons, demand for paperboard cartons in 2050 reaches 281.2 billion cartons, while demand for PET bottles is 234.7 billion. When residual demand is fulfilled entirely by aluminum bottles or stainless-steel bottles, total demand for the substitutes reaches 562.5 million bottles in 2050, while demand for PET bottles grow to 234.7 billion, as in the other cases.

Table 15. Quantity demand in 2023 and 2050 for carton substitution, aluminum substitution, and stainless steel substitution under 50 percent reduction scenario

	Demand	
Carton substitution	**2023**	**2050**
PET bottles	97.1 billion	234.7 billion
Paperboard cartons	0	281.2 billion
Aluminum substitution		
PET bottles	97.1 billion	234.7 billion
Aluminum bottles	0	562.5 million
Stainless steel substitution		
PET bottles	97.1 billion	234.7 billion
Stainless-steel bottles	0	562.5 million
Source: Author's calculations		

In Table 16, average yearly costs, total costs, and the cost difference between each substitution case and business-as-usual are shown. Specifically, substituting PET bottles with paperboard cartons is the most expensive scenario at $737.8 billion, about 70 percent more than business-as-usual. This is because paperboard cartons are costlier to produce than PET bottles per unit but carry the same quantity of water over their lifespan (500 ml). As such, paperboard cartons demonstrate less favorable economic outcomes when used to replace PET bottles. On the other hand, substituting PET bottles with reusable aluminum bottles results in the least total production costs. At $135 billion over the entire period, decreasing PET bottles by 50 percent of business-as-usual projections to 2050 and substituting residual demand with aluminum bottles costs 47 percent less than business-as-usual. Substituting PET bottles with stainless-steel bottles also decreases total costs in comparison to the business-as-usual scenario, but costs are still higher than for aluminum. The results for aluminum and stainless steel substitution highlight the economic benefits of reusable containers.

Table 16. Average yearly costs, total costs, and cost difference between business-as-usual and substitution scenarios under 50 percent reduction

Substitution Scenario	**Average yearly production costs**	**Total costs**	**Cost difference**
Business-as-usual	$12.9 billion	$357.8 billion	
50 percent reduction			
Combined alternatives substitution	$14.2 billion	$398.9 billion	$41.2 billion
Carton substitution	$18.3 billion	$737.8 billion	$380.1 billion
Aluminum substitution	$8.1 billion	$222.7 billion	($135.0 billion)
Stainless steel substitution	$8.3 billion	$231.3 billion	($126.5 billion)
Source: Author's calculations			

In the 90 percent reduction scenario, demand for PET bottles contracts at a rate of 2.4 percent yearly. As in the 50 percent reduction scenario, single-use cartons, reusable aluminum bottles, and reusable stainless-steel bottles are introduced to satisfy an equal proportion of residual demand for packaged water. Total demand for each container type under this scenario in 2023 and 2050 is represented in Table 17. Specifically, demand for PET bottles shrinks from 97 trillion bottles in 2023 to 49.7 trillion in 2050, while demand for paperboard cartons increases to 155.4 billion, and demand for aluminum and stainless-steel bottles increase to 310.8 million.

Table 17. Quantity demand for PET bottles, paperboard cartons, aluminum, and stainless-steel bottles in 2023 and 2050 under 90 percent reduction scenario

	Demand	
Product	**2023**	**2050**
PET bottles	97.1 billion	49.7 billion
Paperboard cartons	0	155.4 billion
Aluminum bottles	0	310.8 million
Stainless steel bottles	0	310.8 million
Source: Author's calculations		

Table 18 reports that the average yearly cost of reducing PET bottles by 90 percent and substituting them with combined alternatives is $15.2 billion. The costliest substitute is paperboard cartons ($11.5 billion per year on average), followed by stainless-steel bottles ($159.2 million per year) and aluminum bottles ($78.8 million per year). Over the period, total costs under this policy scenario are $426.5 billion, about 18 percent greater than business-as-usual production. Predictably, these costs also exceed production costs for the 50 percent reduction scenario, by about $1 billion dollars yearly and $28 billion dollars in total. Relatively high costs are due to the larger volume of residual packaged water demand which must now be fulfilled by higher per unit cost substitutes.

Table 18. Quantity demand and total costs for 28-year period (2023-2050) for PET bottles, paperboard cartons, aluminum, and stainless-steel bottles under 90 percent reduction scenario

Product	**Demand**	**Average yearly production costs**	**Total costs of production**
PET bottles	1.9 trillion	$3.6 billion	$96.7 billion
Paperboard cartons	1.7 trillion	$11.5 billion	$322.6 billion
Aluminum bottles	3.4 billion	$78.8 million	$2.2 billion
Stainless steel bottles	3.4 billion	$159.2 million	$4.5 billion
Total	**3.6 trillion**	**$15.2 billion**	**$426.5 billion**
Source: Author's calculations			

As in the 50 percent reduction scenario, this scenario models substitution by each of the three alternative materials. Table 19 reports the quantity demand for each substitute under each case. If cartons fulfill residual demand for packaged water completely, demand for the container increases from zero in 2023 to 466.2 billion in 2050. Assuming that only aluminum bottles are used, 932.4 million are demanded in 2050. The same amount of stainless-steel bottles are also required under the assumption that stainless-steel fulfills residual demand for packaged water.

Table 19. Quantity demand for carton substitution, aluminum substitution, and stainless steel substitution in 2023 and 2050 under 90 percent reduction scenario

	Demand	
Carton substitution	**2023**	**2050**
PET bottles	97.1 billion	49.7 billion
Cartons	0	466.2 billion
Aluminum substitution		
PET bottles	97.1 billion	49.7 billion
Aluminum bottles	0	932.4 million
Stainless steel substitution		
PET bottles	97.1 billion	49.7 billion
Stainless-steel bottles	0	932.4 million
Source: Author's calculations		

Table 20 reports average yearly costs, total costs, and the cost differential between each substitution case and the business-as-usual scenario. In comparison to the 50 percent reduction scenario, quantity demand and costs for each alternative grow significantly under the 90 percent reduction scenario, due to the increase volume of packaged water that is now fulfilled by the alternatives. Once again, cartons demonstrate the worst economic outcomes in comparison to all other substitutes, costing $1.1 trillion is assumed to be the only alternative to fulfill residual demand for packaged water. Aluminum bottles offer the most economic benefits, costing $103.3 billion and reducing total costs as compared to business-as-usual by 110 percent.

Table 20. Average yearly costs, total costs, and cost difference between business-as-usual and all substitution scenarios under 90 percent reduction

Substitution Scenario	**Average yearly production costs**	**Total costs**	**Cost difference**
BAU	$12.9 billion	$357.8 billion	
90 percent reduction			
Combined alternatives substitution	$15.2 billion	$426.5 billion	$68.7 billion
Carton substitution	$38.2 billion	$1.1 trillion	$711.8 billion
Aluminum substitution	$3.9 billion	$103.3 billion	($254.4 billion)
Stainless steel substitution	$4.1 billion	$115.1 billion	($242.7 billion)
Source: Author's calculations			

The investment required to reduce plastic bottles and shift to substitute containers, as a percent of U.S. GDP, is less than 0.3 percent for all substitution scenarios. Assuming that U.S. GDP grows at an annual rate of 1.5 percent, reducing plastic bottles by 50 percent of business-as-usual and substituting them with ‘combined alternatives’ (paperboard cartons, aluminum bottles, and stainless-steel bottles) costs only 0.02 percent of U.S. total output for the first five years. This proportion slowly increases, but by 2050 accounts for only 0.07 percent of total output. The 90 percent reduction scenario is not much different. Overall costs as a percent of GDP, when substituting to combined alternatives, increase at a faster rate than in the 90 percent reduction scenario, but by 2050 is only slightly larger, at 0.08 percent of U.S. GDP.

Carton substitution, aluminum substitution, and stainless steel substitution scenarios for both 50 percent reduction and 90 percent reduction are also low. The most expensive alternative, when compared to U.S. GDP, is carton substitution, which increases from 0.02 percent of GDP in 2023 to 0.16 percent in 2050, in the 50 percent reduction scenario. In the 90 percent reduction scenario, carton substitution costs increase from 0.02 percent to 0.22 percent of GDP in 2050. The lowest cost options are aluminum substitution and stainless steel substitution. Under the 90 percent reduction scenario, yearly costs for both substitutions as a percent of GDP decline over the 28-year period, from 0.02 percent to 0.01 percent.

Despite the higher per unit costs of aluminum and stainless-steel bottles, their substitution generates significant economic benefits. These benefits are in addition to the environmental advantages that reusable water bottles present. In the current context of mounting environmental damage as a result of plastics production and pollution, switching to reusable non-plastic substitutes could have great consequence for advancing sustainability goals within the U.S.

economy and globally. However, the technical, economic, and environmental opportunities do not negate the substantial social barriers to making such a transition.

8. CONCLUSION

The U.S. has been among the largest consumers of fossil fuel-based single-use plastic bottles, both historically and continuing to the present. This has resulted in large amounts of plastic waste being generated, where it frequently ends up as environmental pollution within the U.S., or overseas as part of the global waste trade. Plastic bottle pollution causes significant environmental damage. Plastic bottles leach toxic chemicals into the soil, water and food supply. These chemicals may be carcinogenic and are linked to fertility issues in humans and other species. Plastic bottles also release tiny 'microplastic' particles, which have been found in several areas of the human body, including the carotid artery tissues that supply blood to the brain. Their presence there is linked to increased likelihood of heart attack, stroke or death. Plastic bottles also accumulate in oceans, litter beaches and roadways, clog water drains, and strangle animals and contaminate their habitats. These issues will intensify if the consumption of plastic bottles continues to grow along the business-as-usual trajectory of roughly 7 percent per year. This would result in an additional 7.1 trillion bottles being used and likely thrown away from 2023 to 2050 within the United States.

This study has highlighted the potential benefits of expanding the use of reusable beverage containers as a strategy to mitigate these environmental impacts. Specifically, I examine six potential alternatives to fossil fuel-derived single-use plastic water bottles. I conclude that reusable aluminum and stainless-steel bottles are the most viable substitutes in the U.S. economy. When reused for a period of 2.5 years, these materials generate much less negative environmental impacts than PET bottles, contribute less to the depletion of fossil fuel resources, CO2 emissions, waste generation, pollution, and toxicity. They also reduce production costs by over 30 percent, when substituting 90 percent of plastic water bottles from business-as-usual projections to 2050; and by over 40 percent, when substituting 50 percent of plastic water bottles from business-as-usual.

These results underscore the environmental and economic benefits associated with expanding the use of reusable aluminum or stainless steel materials for packaging water and other beverages. Facilitating reuse is a critical strategy for plastics policies within the United States. It will also have major global impacts, through sharply reducing the total amount of plastic waste that is generated, mismanaged, and polluted into the global environment.

REFERENCES

2017 Glass Recycling Survey. Glass Recycling Coalition, May 2017, https://static1.squarespace.com/static/61b12c4e31f2761943c9622d/t/61c3ecd58942604fad5ef366/1640230102137/2017-glass-recycling-survey.pdf.

Agamuthu, P., and C. Visvanathan. “Extended Producers’ Responsibility Schemes for Used Beverage Carton Recycling.” *Waste Management & Research*, vol. 32, no. 1, Jan. 2014, pp. 1–3. *SAGE Journals*, https://doi.org/10.1177/0734242X13517611.

Al-Gharrawi, Mohammed Z., et al. “Improving Recycling of Polyethylene-Coated Paperboard with a Nanofibrillated Cellulose Layer.” *BioResources*, vol. 16, no. 2, Mar. 2021, pp. 3285–97. *DOI.org (Crossref)*, https://doi.org/10.15376/biores.16.2.3285-3297.

Amienyo, David, et al. “Life Cycle Environmental Impacts of Carbonated Soft Drinks.” *The International Journal of Life Cycle Assessment*, vol. 18, 2013, https://link.springer.com/article/10.1007/s11367-012-0459-y.

Aristi Capetillo, Alejandro, et al. “Emerging Technologies Supporting the Transition to a Circular Economy in the Plastic Materials Value Chain.” *Circular Economy and Sustainability*, vol. 3, no. 2, June 2023, pp. 953–82. *Springer Link*, https://doi.org/10.1007/s43615-022-00209-2.

Aslani, Hassan, et al. “Tendencies towards Bottled Drinking Water Consumption: Challenges Ahead of Polyethylene Terephthalate (PET) Waste Management.” *Health Promotion Perspectives*, vol. 11, no. 1, Feb. 2021, pp. 60–68. *PubMed Central*, https://doi.org/10.34172/hpp.2021.09.

Azoulay, David, et al. *Plastic & Health: The Hidden Costs of a Plastic Planet*. Center for International Environmental Law, Feb. 2019, https://www.ciel.org/wp-content/uploads/2019/02/Plastic-and-Health-The-Hidden-Costs-of-a-Plastic-Planet-February-2019.pdf.

Barrowclough, Diana, and Carolyn Deere Birkbeck. *Transforming the Global Plastics Economy: The Political Economy and Governance of Plastics Production and Pollution*. Working Paper, 142, GEG Working Paper, 2020. *www.econstor.eu*, https://www.econstor.eu/handle/10419/224117.

Becerra-Galicia, Susana Angelina. *Low-Waste Drinking Water Consumption Through Nudging*. 2022. Arizona State University.

Beverage Marketing Corporation. *Press Release: Bottled Water Volume Growth Slows in 2022, Data from Beverage Marketing Corporation Show*. May 2023, https://www.beveragemarketing.com/news-detail.asp?id=746.

Bioplastics Market Development Update 2023. European Bioplastics, Dec. 2023, https://docs.european-bioplastics.org/publications/market_data/2023/EUBP_Market_Data_Report_2023.pdf.

Björkman, Bo, and Caisa Samuelsson. “Chapter 6 - Recycling of Steel.” *Handbook of Recycling*, edited by Ernst Worrell and Markus A. Reuter, Elsevier, 2014, pp. 65–83. *ScienceDirect*, https://doi.org/10.1016/B978-0-12-396459-5.00006-4.

Bouhlel, Zeineb, et al. *Global Bottled Water Industry: A Review of Impacts and Trends*. United Nations University: Institute for Water, Environment, and Health, 2023. *DOI.org (Crossref)*, https://doi.org/10.53328/AGYM7357.

Bradley, Paul M., et al. “Bottled Water Contaminant Exposures and Potential Human Effects.” *Environment International*, vol. 171, Jan. 2023, p. 107701. *ScienceDirect*, https://doi.org/10.1016/j.envint.2022.107701.

Breault, Philip. *Carton Recycling Primer*. Carton Council, Mar. 2015.

Brock, A., and I. D. Williams. *Life Cycle Assessment of Drinks Packaging: Are There Environmentally-Friendly Alternatives to Plastics?* 2019.

Brouwer, Marieke T., et al. "Effect of recycled content and rPET quality on the properties of PET bottles, part III: Modelling of repetitive recycling." *Packaging Technology and Science*, vol. 33, no. 9, 2020, pp. 373–83. *Wiley Online Library*, https://doi.org/10.1002/pts.2489.

Capuzzi, Stefano, and Giulio Timelli. "Preparation and Melting of Scrap in Aluminum Recycling: A Review." *Metals*, vol. 8, no. 4, 4, Apr. 2018, p. 249. *www.mdpi.com*, https://doi.org/10.3390/met8040249.

Carton Service. *The Future of Sustainable Packaging: Gable Top Cartons*. Dec. 2021, https://www.cartonservice.com/blog/the-future-of-sustainable-packaging-gable-top-cartons/.

Center for Disease Control. *History of Drinking Water Treatment*. 10 Oct. 2018, https://www.cdc.gov/healthywater/drinking/history.html.

Chakrabortty, Aditya. "Secret Report: Biofuel Caused Food Crisis." *The Guardian*, 3 July 2008. *The Guardian*, https://www.theguardian.com/environment/2008/jul/03/biofuels.renewableenergy.

Chen, Luyi, et al. "Comparative Life Cycle Assessment of Fossil and Bio-Based Polyethylene Terephthalate (PET) Bottles." *Journal of Cleaner Production*, vol. 137, Nov. 2016, pp. 667–76. *ScienceDirect*, https://doi.org/10.1016/j.jclepro.2016.07.094.

Chen, Wei-Qiang. "Recycling Rates of Aluminum in the United States." *Journal of Industrial Ecology*, vol. 17, no. 6, 2013, pp. 926–38. *Wiley Online Library*, https://doi.org/10.1111/jiec.12070.

Chiba, Taiyo, et al. "Socioeconomic Factors Influencing Global Paper and Paperboard Demand." *Journal of Wood Science*, vol. 63, no. 5, Oct. 2017, pp. 539–47. *Springer Link*, https://doi.org/10.1007/s10086-017-1648-x.

Cost Competitiveness of PET, Aluminium, and Glass Beverage Containers. International Aluminium, Sept. 2022, https://international-aluminium.org/wp-content/uploads/2022/09/Cost-competitiveness-of-PET-aluminium-and-glass-beverage-containers-1.pdf.

Cullen, Jonathan M., and Julian M. Allwood. "Mapping the Global Flow of Aluminum: From Liquid Aluminum to End-Use Goods." *Environmental Science & Technology*, vol. 47, no. 7, Apr. 2013, pp. 3057–64. *ACS Publications*, https://doi.org/10.1021/es304256s.

Das, Subodh K., et al. "Aluminum Recycling: Economic and Environmental Benefits." *LIGHT METAL AGE*, 2010.

Deshwal, Gaurav Kr., and Narender Raju Panjagari. "Review on Metal Packaging: Materials, Forms, Food Applications, Safety and Recyclability." *Journal of Food Science and Technology*, vol. 57, no. 7, July 2020, pp. 2377–92. *Springer Link*, https://doi.org/10.1007/s13197-019-04172-z.

Duan, Chenxingyu, et al. "Global Polyethylene Terephthalate (PET) Plastic Supply Chain Resource Metabolism Efficiency and Carbon Emissions Co-Reduction Strategies." *Sustainability*, vol. 16, no. 10, 10, Jan. 2024, p. 3926. *www.mdpi.com*, https://doi.org/10.3390/su16103926.

Eckert, Sandra. "Varieties of Framing the Circular Economy and the Bioeconomy: Unpacking Business Interests in European Policymaking." *Journal of Environmental Policy & Planning*, vol. 23, no. 2, Mar. 2021, pp. 181–93. *Taylor and Francis+NEJM*, https://doi.org/10.1080/1523908X.2021.1894106.

Environmental Working Group. *Timeline: BPA from Invention to Phase-Out*. 22 Apr. 2008, https://www.ewg.org/research/timeline-bpa-invention-phase-out.

European Bioplastics. "Environment." *European Bioplastics e.V.*, https://www.european-bioplastics.org/bioplastics/environment/. Accessed 30 Sept. 2024.

EUWID. *Markets - Cartonboard UK*. https://www.euwid-packaging.com/markets/cartonboard-uk/. Accessed 30 Sept. 2024.

Gironi, F., and V. Piemonte. "Bioplastics and Petroleum-Based Plastics: Strengths and Weaknesses." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 33, no. 21, Aug. 2011, pp. 1949–59. *DOI.org (Crossref)*, https://doi.org/10.1080/15567030903436830.

[a] Glass Packaging Institute. *Facts About Glass*. n.d., https://www.gpi.org/facts-about-glass.

[b] Glass Packaging Institute. *Glass Recycling Facts*. n.d., https://www.gpi.org/glass-recycling-facts.

Gleick, Peter H. *Bottled and Sold: The Story Behind Our Obsession with Bottled Water*. Island Press, 2010.

Global Package. *An Insight into the Glass Bottle Manufacturing Process*. 10 Dec. 2023, https://globalpackage.net/an-insight-into-the-glass-bottle-manufacturing-process/.

Goldstein, Nora, et al. "BioCycle Nationwide Survey: Full-Scale Food Waste Composting Infrastructure In The U.S." *BioCycle*, 25 July 2023, https://www.biocycle.net/us-food-waste-composting-infrastructure/.

Hawkins, Gay. "Packaging Water: Plastic Bottles as Market and Public Devices." *Economy and Society*, vol. 40, no. 4, Nov. 2011, pp. 534–52. *Taylor and Francis+NEJM*, https://doi.org/10.1080/03085147.2011.602295.

Hawkins, Gay. "The Impacts of Bottled Water: An Analysis of Bottled Water Markets and Their Interactions with Tap Water Provision." *WIREs Water*, vol. 4, no. 3, 2017, p. e1203. *Wiley Online Library*, https://doi.org/10.1002/wat2.1203.

Industrial Metal Service. *Aluminum vs. Stainless Steel: A Comprehensive Comparison*. 21 Feb. 2024, https://industrialmetalservice.com/metal-university/aluminum-vs-stainless-steel/.

Industry Statistics: Facts at a Glance 2018. The Aluminum Association, Jan. 2020, https://www.aluminum.org/sites/default/files/2021-11/FactSheet2018.pdf.

Intratec. *Stainless Steel Prices*. https://www.intratec.us/chemical-markets/stainless-steel-price. Accessed 16 Sept. 2024.

[a] International Bottled Water Association. *Bottled Water Reaches New Peaks in Revenue and Volume*. n.d., https://bottledwater.org/nr/bottled-water-reaches-new-peaks-in-revenue-and-volume/.

[b] International Bottled Water Association. *Packaging*. n.d., https://bottledwater.org/packaging/.

International Energy Agency. *Iron and Steel Technology Roadmap*. 8 Oct. 2020, https://www.iea.org/reports/iron-and-steel-technology-roadmap.

[a] International Energy Agency. *Aluminium*. https://www.iea.org/energy-system/industry/aluminium. Accessed 7 Aug. 2024.

[b] International Energy Agency. *Average GHG Emissions Intensity for Production of Selected Commodities*. https://www.iea.org/data-and-statistics/charts/average-ghg-emissions-intensity-for-production-of-selected-commodities. Accessed 17 Aug. 2024.

Jacoby, Mitch. "Why Glass Recycling in the US Is Broken." *Chemical & Engineering News*, 11 Feb. 2019, https://cen.acs.org/materials/inorganic-chemistry/glass-recycling-US-broken/97/i6.

Jamshidian, Majid, et al. “Poly-Lactic Acid: Production, Applications, Nanocomposites, and Release Studies.” *Comprehensive Reviews in Food Science and Food Safety*, vol. 9, no. 5, 2010, pp. 552–71. *Wiley Online Library*, https://doi.org/10.1111/j.1541-4337.2010.00126.x.

Javidani, Mousa, et al. “Processing Techniques and Metallurgical Perspectives and Their Potential Correlation in Aluminum Bottle Manufacturing for Sustainable Packaging Solutions.” *Crystals*, vol. 14, no. 5, 5, May 2024, p. 434. *www.mdpi.com*, https://doi.org/10.3390/cryst14050434.

Johnson, Jeremiah, et al. “The Energy Benefit of Stainless Steel Recycling.” *Energy Policy*, vol. 36, no. 1, Jan. 2008, pp. 181–92. *ScienceDirect*, https://doi.org/10.1016/j.enpol.2007.08.028.

Kim, Jinsoo, et al. “Decarbonizing the Iron and Steel Industry: A Systematic Review of Sociotechnical Systems, Technological Innovations, and Policy Options.” *Energy Research & Social Science*, vol. 89, July 2022, p. 102565. *ScienceDirect*, https://doi.org/10.1016/j.erss.2022.102565.

Kinsella, Susan, et al. *The State of the Paper Industry: Monitoring the Indicators of Environmental Performance*. The Environmental Paper Network, 2007, https://environmentalpaper.org/wp-content/uploads/2017/08/state-of-the-paper-industry-2007-full.pdf#page=13.14.

Kirwan, Mark J. *Handbook of Paper and Paperboard Packaging Technology*. John Wiley & Sons, 2012.

Life Cycle Inventory of Three Single Serving Soft Drink Containers. Franklin Associates, 2009, https://pieweb.plasteurope.com/members/pdf/p215957b.PDF.

Lundell, Clark, and Joyce Thomas. “PET: Polyethylene Terephthalate – The Ubiquitous 500 Ml Water Bottle.” *Advances in Industrial Design*, edited by Giuseppe Di Bucchianico et al., Springer International Publishing, 2020, pp. 248–54. *Springer Link*, https://doi.org/10.1007/978-3-030-51194-4_33.

Mah, Alice. *How Corporations Are Fuelling the Ecological Crisis and What We Can Do About It*. Polity Books, 2022, https://www.politybooks.com/plastic-unlimited/.

Marfella Raffaele, et al. “Microplastics and Nanoplastics in Atheromas and Cardiovascular Events.” *New England Journal of Medicine*, vol. 390, no. 10, Mar. 2024, pp. 900–10. *Taylor and Francis+NEJM*, https://doi.org/10.1056/NEJMoa2309822.

Mills, Jess. “Glass Collection Rate in EU Reaches 80.2%.” *Glass International*, 28 June 2024, https://www.glass-international.com/news/glass-collection-rate-in-eu-reaches-80-2.

Mineral Commodity Summaries 2024. US Geological Survey, Jan. 2024, pp. 42–43.
Mujtaba, Muhammad, et al. “Trends and Challenges in the Development of Bio-Based Barrier Coating Materials for Paper/Cardboard Food Packaging; *a Review*.” *Science of The Total Environment*, vol. 851, Dec. 2022, p. 158328. *ScienceDirect*, https://doi.org/10.1016/j.scitotenv.2022.158328.

OECD. *Improving Markets for Recycled Plastics: Trends, Prospects and Policy Responses*. OECD, 2018. *DOI.org (Crossref)*, https://doi.org/10.1787/9789264301016-en.

Papong, Seksan, et al. “Comparative Assessment of the Environmental Profile of PLA and PET Drinking Water Bottles from a Life Cycle Perspective.” *Journal of Cleaner Production*, vol. 65, Feb. 2014, pp. 539–50. *ScienceDirect*, https://doi.org/10.1016/j.jclepro.2013.09.030.

Pathwater. *Sustainable Bottled Water, the PATHWATER Life Cycle Assessment*. 27 Aug. 2019, https://drinkpathwater.com/blogs/news/sustainable-bottled-water-the-pathwater-life-cycle-assessment.

Persico, Lavinia Pia. *Life Cycle Impacts of Aseptic Carton Used for Drinking Water Delivery*. 2019. SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING. *www.politesi.polimi.it*, https://www.politesi.polimi.it/handle/10589/154534.

Plastics News. “Resin Prices.” *Plastics News*, 1 May 2023, https://www.plasticsnews.com/resin-prices.

Raabe, Dierk, et al. “Making Sustainable Aluminum by Recycling Scrap: The Science of ‘Dirty’ Alloys.” *Progress in Materials Science*, vol. 128, July 2022, p. 100947. *ScienceDirect*, https://doi.org/10.1016/j.pmatsci.2022.100947.

Ragusa, Antonio, et al. “Plasticenta: First Evidence of Microplastics in Human Placenta.” *Environment International*, vol. 146, Jan. 2021, p. 106274. *ScienceDirect*, https://doi.org/10.1016/j.envint.2020.106274.

Raj, Sean D. “Bottled Water: How Safe Is It?” *Water Environment Research*, vol. 77, no. 7, 2005, pp. 3013–18. *Wiley Online Library*, https://doi.org/10.2175/106143005X73893.

Reusable Water Bottle Market Size & Share Report, 2030. https://www.grandviewresearch.com/industry-analysis/reusable-water-bottle-market. Accessed 9 Aug. 2024.

Rezvani Ghomi, Erfan, et al. “The Life Cycle Assessment for Polylactic Acid (PLA) to Make It a Low-Carbon Material.” *Polymers*, vol. 13, no. 11, June 2021, p. 1854. *PubMed Central*, https://doi.org/10.3390/polym13111854.

Rodwan Jr., John. *Significant, but Slower, Growth for Bottled Water in 2018*. International Bottled Water Association, Aug. 2019, https://bottledwater.org/statistics/.

Rosenboom, Jan-Georg, et al. “Bioplastics for a Circular Economy.” *Nature Reviews Materials*, vol. 7, no. 2, Feb. 2022, pp. 117–37. *www.nature.com*, https://doi.org/10.1038/s41578-021-00407-8.

Saevarsdottir, Gudrun, et al. “Aluminum Production in the Times of Climate Change: The Global Challenge to Reduce the Carbon Footprint and Prevent Carbon Leakage.” *JOM*, vol. 72, no. 1, Jan. 2020, pp. 296–308. *Springer Link*, https://doi.org/10.1007/s11837-019-03918-6.

Scrapmonster. *Standard Plate Price*. https://www.scrapmonster.com/steel-prices/standard-plate-prices/595#google_vignette. Accessed 30 Sept. 2024.

Silva, Jorge Alejandro. “Ethics of Manufacturing and Supplying Bottled Water: A Systematic Review.” *Sustainability*, vol. 16, no. 8, 8, Jan. 2024, p. 3488. *www.mdpi.com*, https://doi.org/10.3390/su16083488.

Simon, Bálint, et al. “Life Cycle Impact Assessment of Beverage Packaging Systems: Focus on the Collection of Post-Consumer Bottles.” *Journal of Cleaner Production*, vol. 112, Jan. 2016, pp. 238–48. *ScienceDirect*, https://doi.org/10.1016/j.jclepro.2015.06.008.

Sims, Ralph E. H., et al. “An Overview of Second Generation Biofuel Technologies.” *Bioresource Technology*, vol. 101, no. 6, Mar. 2010, pp. 1570–80. *ScienceDirect*, https://doi.org/10.1016/j.biortech.2009.11.046.

“Single Wall Stainless Steel Water Bottle with Lid.” *Ethika Inc*, https://ethikainc.com/products/single-wall-stainless-steel-water-bottle-with-stainless-steel-lid-3-sizes-available. Accessed 26 Aug. 2024.

Souder, James, et al. *Recycling Unpacked: Assessing the Circular Potential of Beverage Containers in the US*. Metabolic, Oct. 2020, https://www.cancentral.com/wp-content/uploads/2023/01/Metabolic_Report_RecyclingUnpacked.pdf.

Steel Profile. American Iron and Steel Institute, https://www.steel.org/wp-content/uploads/2024/01/AISI-Profile-Book_updated-3.2023.pdf. Accessed 9 Aug. 2024.

Stegmann, Paul, et al. “Plastic Futures and Their CO2 Emissions.” *Nature*, vol. 612, no. 7939, 7939, Dec. 2022, pp. 272–76. *www.nature.com*, https://doi.org/10.1038/s41586-022-05422-5.

Stramarkou Marina, et al. “Comparative Life Cycle Assessment of Polyethylene Terephthalate (Pet) and Multilayer Tetra Pak Juice Packaging Systems.” *Chemical Engineering Transactions*, vol. 87, July 2021, pp. 103–08. *DOI.org (CSL JSON)*, https://doi.org/10.3303/CET2187018.

Tabone, Michaelangelo D., et al. “Sustainability Metrics: Life Cycle Assessment and Green Design in Polymers.” *Environmental Science & Technology*, vol. 44, no. 21, Nov. 2010, pp. 8264–69. *ACS Publications*, https://doi.org/10.1021/es101640n.

Tamburini, Elena, et al. “Plastic (PET) vs Bioplastic (PLA) or Refillable Aluminium Bottles – What Is the Most Sustainable Choice for Drinking Water? A Life-Cycle (LCA) Analysis.” *Environmental Research*, vol. 196, May 2021, p. 110974. *ScienceDirect*, https://doi.org/10.1016/j.envres.2021.110974.

Taylor, Brian. “McKinsey Says PET Scrap Collection Needs Boost in US.” *Recycling Today*, 6 Sept. 2023, https://www.recyclingtoday.com/news/pet-plastic-recycling-shortage-usa-mckinsey-research-2023/.

Todorova, D. A., et al. “Paperboard Packaging for Liquid Foods.” *Journal of Food and Packaging: Science, Technique, and Technologies*, 2015, pp. 29–34.

US Bureau of Labor Statistics. *Average Energy Prices for the United States, Regions, Census Divisions, and Selected Metropolitan Areas*. https://www.bls.gov/regions/midwest/data/averageenergyprices_selectedareas_table.htm. Accessed 9 Aug. 2024.

US Energy Information Administration. *Today in Energy*. 21 Aug. 2013, https://www.eia.gov/todayinenergy/detail.php?id=12631.

US Environmental Protection Agency. *US Container Glass Industry Carbon Intensities (2019)*. 21 May 2022, https://www.epa.gov/system/files/documents/2022-06/2019%20Container%20Glass%20Plant%20Carbon%20Intensities%20Fact%20Sheet%20.pdf.

[a] US Environmental Protection Agency. *Plastics: Material-Specific Data*. 12 Sept. 2017, https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data.

[b] US Environmental Protection Agency. *Glass: Material-Specific Data*. 7 Sept. 2017, https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/glass-material-specific-data.

[c] US Environmental Protection Agency. *Aluminum: Material-Specific Data*. 7 Sept. 2017, https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/aluminum-material-specific-data.

[d] US Environmental Protection Agency. *Containers and Packaging: Product-Specific Data*. 7 Sept. 2017, https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/containers-and-packaging-product-specific.

Valois, Michael. *UNECE/FAO Data Brief 2023: Pulp, Paper and Paperboard*. United Nations and Food and Agricultural Organization of the United States, 2023, https://unece.org/sites/default/files/2023-11/2023-data-brief-pap-final-web_1.pdf.

von Falkenstein, Eva, et al. “LCA Studies Comparing Beverage Cartons and Alternative Packaging: Can Overall Conclusions Be Drawn?” *The International Journal of Life Cycle Assessment*, vol. 15, no. 9, Nov. 2010, pp. 938–45. *Springer Link*, https://doi.org/10.1007/s11367-010-0218-x.

Wellenreuther, Claudia, et al. “Cost Competitiveness of Sustainable Bioplastic Feedstocks – A Monte Carlo Analysis for Polylactic Acid.” *Cleaner Engineering and Technology*, vol. 6, Feb. 2022, p. 100411. *ScienceDirect*, https://doi.org/10.1016/j.clet.2022.100411.

Willis, Kathryn, et al. "The Success of Water Refill Stations Reducing Single-Use Plastic Bottle Litter." *Sustainability*, vol. 11, no. 19, 19, Jan. 2019, p. 5232. *www.mdpi.com*, https://doi.org/10.3390/su11195232.

World Steel. *Stainless Steels and CO2: Industry Emissions and Related Data*. 2023, https://www.worldstainless.org/about-stainless/environment/stainless-steels-and-co2-industry-emissions-and-related-data/.