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Climate impact of plastics

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Contents

Plastics are frequently criticized for everything from their toxicity to their contributions to ocean pollution, but they play an important role in enhancing use efficiencies and reducing greenhouse gas emissions.

1. Summary: Plastics have a lower total greenhouse gas contribution than alternatives in most applications

by David Feber, Stefan Helmcke, Thomas Hundertmark, Chris Musso, Wen Jie Ong, Jonas Oxgaard, and Jeremy Wallach

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Plastics are ubiquitous across the global economy and are the subject of frequent debate, from their impact on marine pollution to their recyclability. However, their role in enhancing use efficiencies, such as decreasing food spoilage and reducing greenhouse gas (GHG) emissions, is often overlooked. Rather, plastics are frequently maligned regarding topics such as leakage to the environment, toxicity, use of resources, production emissions, and ocean pollution. Although these important considerations need to be addressed, an opportunity exists for a more balanced, science-based perspective on plastics versus alternative materials.

Multiple environmental factors should be considered in material selection. This paper examines the total GHG contribution of plastics versus its alternatives, including product life cycle (cradle to grave) and impact of use, but does not consider ocean pollution, which needs to be addressed separately. Our objective is to contribute to the dialogue on material choice and broaden the available fact base for the evolving discussion around plastics.

Our analysis is based on the United States in 2020, with sensitivities to illustrate the impact in other regions and how results will change as we move toward a decarbonized world in 2050. Findings vary by regions, given the different energy mix and end-of-life treatments, such as recycling. As part of our methodology, we looked closely at examples from five sectors with the highest consumption of plastics—packaging, building and construction, automotive, textiles, and consumer durables—representing around 90 percent of global plastics volume. We also selected representative applications for which at-scale, viable choices between plastics and alternatives exist today, avoiding niche or new solutions.

Among applications for which nonplastic alternatives are used at scale, the plastics examined in this paper offer a lower total GHG contribution compared with alternatives in 13 of 14 cases. GHG savings range from 10 to 90 percent, considering both product life cycle and impact of use. In addition, in many applications, particularly those concentrated in food packaging, there are few alternatives to plastics today. In fact, plastics adoption in the near term can help decarbonization efforts in these areas, particularly in terms of food spoilage and energy efficiency, given their lower GHG footprint.

In a low-carbon, high-circularity economy,[1] the benefits of plastics relative to materials such as aluminum diminish. Europe may have already achieved such a low-carbon, high-circularity economy, and according to a recent McKinsey report, *The net-zero transition: What it would cost, what it could bring*, the entire global economy can shift in this direction as industries transition toward a decarbonized world by 2050.[2]

Finally, we once again highlight that the benefits of plastics do not diminish the industry's need to continue improving environmental performance, including meeting net-zero targets, achieving significant improvements in recycling, and eliminating leakage to the environment.

[1] For more on the circular economy, see "What is a circular economy?," Ellen MacArthur Foundation, accessed May 16, 2022.
[2] "The net-zero transition: What it would cost, what it could bring," McKinsey, accessed May 16, 2022.

2. Context: Climate impact as one element of the plastics debate

Plastics are arguably among the most revolutionary materials humanity has invented. They are low-cost yet lightweight, durable, and highly customizable. However, one could also argue that plastic is now a victim of its own success, with increasing criticism of marine pollution, roadside litter, fossil feedstock use, and lack of recycling. These are important considerations, and we all share a responsibility to address these issues. We believe, however, that there is one aspect of this conversation that has not received the attention it deserves: the environmental benefits plastics bring compared with alternatives, especially in relation to GHG emissions.

GHG emissions are increasingly important, given the need to dramatically reduce anthropogenic carbon emissions to limit warming to 1.5 degrees Celsius above preindustrial levels to avoid the worst impacts of climate change.[3] The debate on materials choice should take a balanced and science-based perspective and include the emissions profile as one factor. This does not diminish society's need to address waste leakage or promote circularity but does add another perspective.

This paper uses a life cycle approach to comprehensively assess GHG emissions of plastics versus alternative materials. The goal is not to create a detailed ISO-compliant[4] life cycle assessment (LCA) method framework for each application analyzed but to assess the climate impact of plastics across a broad range of applications with enough rigor to be representative, comprehensive, and meaningful. Ideally, this work can provide additional perspective on the sustainability of plastics by including the lenses of GHG emissions and life cycle analysis in the plastics sustainability dialogue and by providing context and science-based arguments that can be used in future discussions. We recognize there is significant complexity within each application, and there are variabilities in the underlying assumptions, including emissions factors, end-of-life treatment, and emissions during product use. This report represents a best effort to provide an accurate, realistic depiction of plastic climate impact.

While the findings are broadly in line with published reports,[5] we believe we offer unique insights in two ways:

— *A broader assessment of the climate impact of plastics for representative applications across many major plastic use categories.* We analyzed 14 applications in which the alternatives to plastic are nonplastics such as metal or glass and an additional two test applications in which the plastic alternative is a plastics-enabled mix of materials. In sum, these applications are representative of approximately 90 percent of all plastics used.

— *Sensitivity analyses showing the impact of the different energy mixes, recycling rates, and transport fuels.* We believe these analyses provide insight into the complexity of the problem and how plastics versus alternatives will evolve in the years to come.

[3] *Global Warming of 1.5°C: An IPCC [Intergovernmental Panel on Climate Change] Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, Intergovernmental Panel on Climate Change, 2019.
[4] "ISO" refers to International Organization for Standardization. For more, see "Standards," ISO, accessed May 16, 2022.
[5] *Innovations for greenhouse gas reductions: A life cycle quantification of carbon abatement solutions enabled by the chemical industry*, International Council of Chemical Associations (ICCA), 2009; Bernd Brandt, Roland Fehringer, and Harald Pilz, *The impact of plastics on life cycle energy consumption and greenhouse gas emissions in Europe*, Denkstatt, June 2010; Rick Lord et al., *Plastics and sustainability: A valuation of environmental benefits, costs and opportunities for continuous improvement*, Trucost, July 2016; *Life cycle impacts of plastic packaging compared to substitutes in the United States and Canada: Theoretical substitution analysis*, Franklin Associates, April 2018.

3. Methodology: Plastics versus alternatives across life cycle and impact of use

Our analysis compares the total direct and indirect GHG emissions from plastics and alternative materials in 14 applications with nonplastic alternatives and two applications with plastics-enabled mix alternatives. All applications were drawn from the full spectrum of plastic usage.

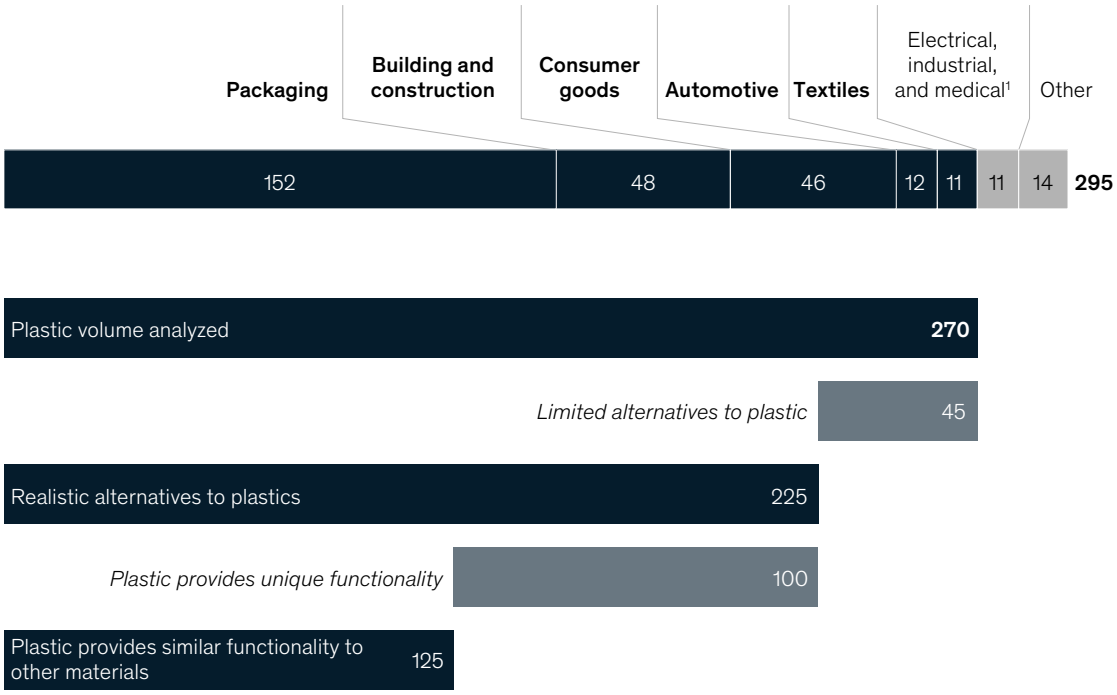
Applications selected from the full spectrum of plastics

In selecting applications for our analyses, we first segmented global plastic demand into sectors. In 2020, global plastic demand was approximately 295 million metric tons (MMT), of which the top five sectors with the highest plastic consumption—packaging, building and construction, consumer goods, automotive, and textiles—accounted for 270 MMT, or close to 90 percent of total volume (Exhibit 1). We further segmented the top five sectors into application categories and evaluated the prevalence of nonplastic alternatives in each category.

Exhibit 1

We selected application categories based on the top five sectors with the highest plastics consumption.

2020 global plastic demand, million metric tons



Note: Figures may not sum, because of rounding.
[1] Electrical accounts for 6.05 million metric tons, medical accounts for 5.14, and industrial accounts for 0.29.
Source: McKinsey Chemical Insights

For some application categories—such as automotive interiors, caps and closures, appliances, and electronics—the market currently has few, if any, plastic alternatives. These categories account for approximately 45 MMT of total plastics volume. For the remaining categories, in which there is a realistic choice between plastic and nonplastic alternatives—such as rigid food packaging, pipes, and automotive powertrains—we assessed the GHG impact by selecting one or more representative applications (Exhibit 2). The choice of which products and materials to assess was based on market share (particularly in the United States) of products used at scale today and excluded nascent or niche solutions.

In some categories, there are applications with majority market shares—for example, in building insulation, we compared polyurethane with glass fiber because together, the two materials cover approximately 80 percent of new-build construction.[6] In categories that lack a dominant application, we selected representative examples, such as a refillable soap bottle as an example of rigid nonfood packaging. While a soap bottle does not represent the entire category of rigid nonfood packaging, it may provide an example of the space. In the automotive space, we chose to consider fuel tanks in hybrid vehicles, rather than in internal-combustion-engine (ICE) vehicles, because the hybrid market is expected to grow in the coming years relative to ICE vehicles and fuel tanks on hybrids and ICE vehicles are a similar size.

We cover a range of both plastics and nonplastics materials. We compare plastic to non-bio alternatives—such as steel, glass, aluminum, glass fiber, copper, concrete, and ductile iron—and to bio alternatives such as paper, wood, cotton, and wool. We omitted other materials and comparisons due to low market share or limited availability of reliable use data. For example, we chose to focus on plastic and paper grocery bags, excluding reusable grocery bags due to the wide array of volumes and materials used and a lack of reliable data about reuse, which has a critical impact on the life cycle of these alternatives. We also chose to exclude compostable and biodegradable alternatives; although these alternatives hold promise for reducing GHG emissions, they currently account for less than 1 percent of the plastics market (at approximately two million tons annually).[7] Importantly, none of the applications were chosen to favor plastics. Instead, we selected applications to cover the full range of plastic uses before we performed any analysis. Indeed, as we show in the "Overall findings" section, plastics are not the lowest GHG emissions choice in every category.

Finally, we included two applications in which plastic competes with plastic-enabled alternatives: water cups and milk containers. In both applications, the alternative to plastic is a mix of approximately 80 percent paper and 20 percent plastic. This means it's not a pure comparison between plastic and nonplastic materials. Nevertheless, we have included them here because these applications came up frequently in discussions as good examples, and we felt that excluding them would mean omitting an important alternative space.

Total GHG contribution: Inclusion of indirect value-chain impacts in the life cycle approach

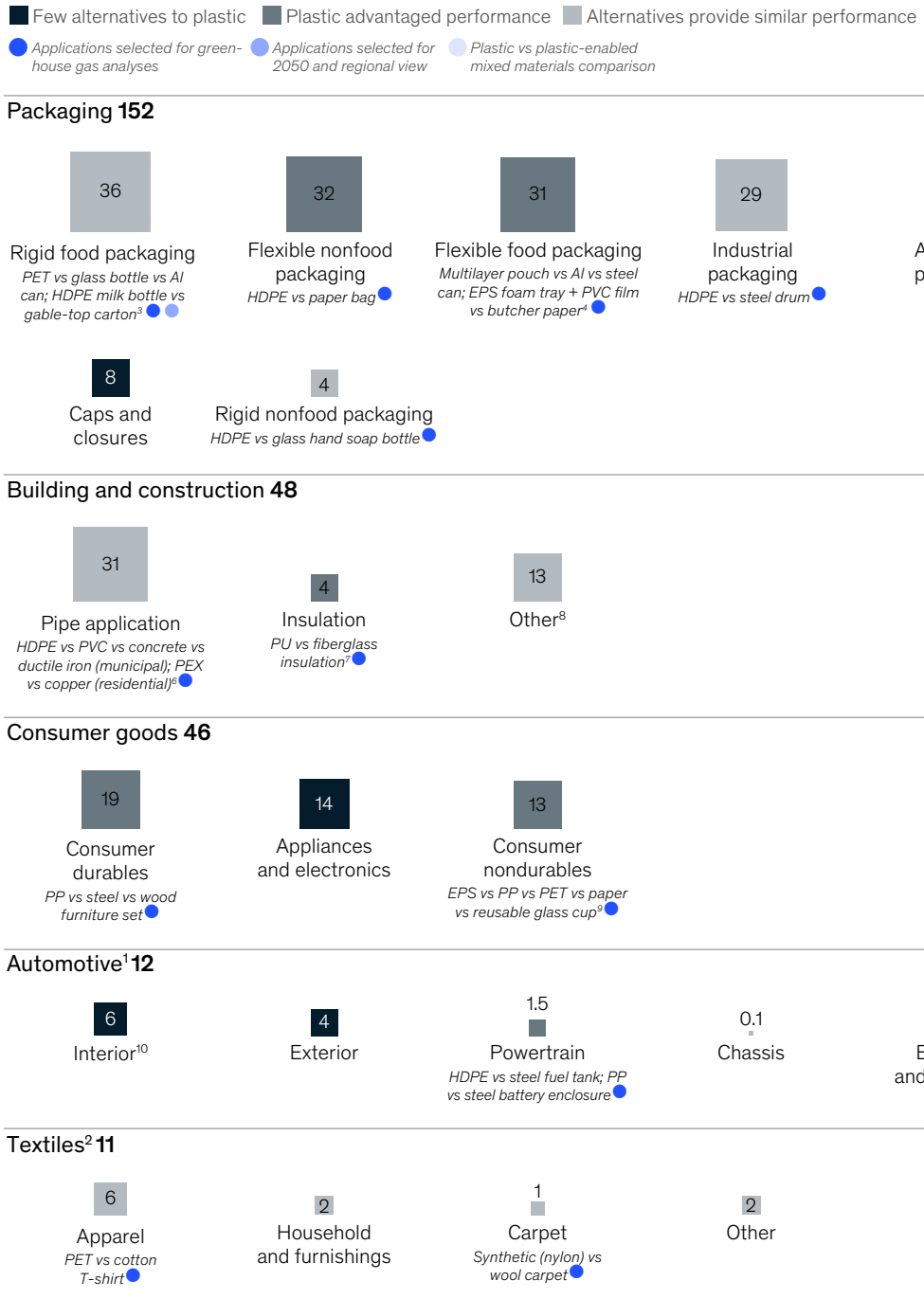
Informed by ISO 14040/44 principles,[8] we adopted a life cycle approach to assess the climate impact of representative plastic applications versus common real-world alternatives. Our application selection was judicious to cover the full spectrum of the plastics space (see the previous section, "Applications selected from the full spectrum of plastics"). We based our GHG assessments on 2020 conditions in the United States, with sensitivity analyses extending to other regions, such as Western Europe and China, thus creating a 2050 view of a decarbonized and circular world. Our decision to base our analyses on the United States stemmed from the availability of data and the fact that the US energy mix and end-of-life disposition

[6] *Global residential insulation market: Analysis by material (fiberglass, foamed plastic, mineral wool, others), project type, area of building, housing type, by region, by country: Market insights, Covid-19 impact, competition and forecast*, Azoth Analytics, October 2020.
[7] "Bioplastics market growth projected at 12% CAGR during the period 2022-2027," Mordor Intelligence, March 22, 2022.
[8] "ISO 14040:2006: Environmental management — Life cycle assessment — Principles and framework," International Organization for Standardization (ISO), 2006.

Exhibit 2

We created detailed greenhouse gas assessments for selected applications within each application category.

2020 global plastic demand, million metric tons



Note: Figures may not sum, because of rounding.
[1] Breakdown of plastic volume based on a midsize sedan car (eg, 2018 Honda Accord). [2] Breakdown of plastic volume estimated using 2010 market share. [3] PET is polyethylene terephthalate; Al is aluminum; HDPE is high-density polyethylene. [4] EPS is expanded polystyrene; PVC is polyvinyl chloride. [5] Includes packaging film, sheets, raffia, filament, and fiber. [6] PEX is cross-linked polyethylene. [7] PU is polyurethane. [8] Includes floor, fixture, liner, and frame. [9] PP is polypropylene. [10] Includes heating and cooling system.
Source: A2Mac1; Independent Commodity Intelligence Services (ICIS); McKinsey Chemical Insights

are close to the global average.[9] We leveraged the US Environmental Protection Agency's Waste Reduction Model (WARM)[10] as our primary life cycle inventory data source, augmenting it with data from the ecoinvent database v3.7[11] and other published LCAs. Two independent LCA experts reviewed our approach, analyses, and findings to ensure that our methodology was scientifically sound and that our assumptions and data sources were robust and reliable.

The details of our methodology are summarized below:

— *Functional units:* A functional unit is the quantified performance of a product system used as a reference in an LCA. For example, the functional unit for a beverage container can be defined as the given volume of the beverage. We attempted to ensure that product-level comparisons within each application are fair and reasonable, using the definition of functional units in published LCAs where appropriate and accounting for product life spans—for example, the five-year life span of a high-density polyethylene (HDPE) industrial drum versus the ten-year life span of a steel drum.

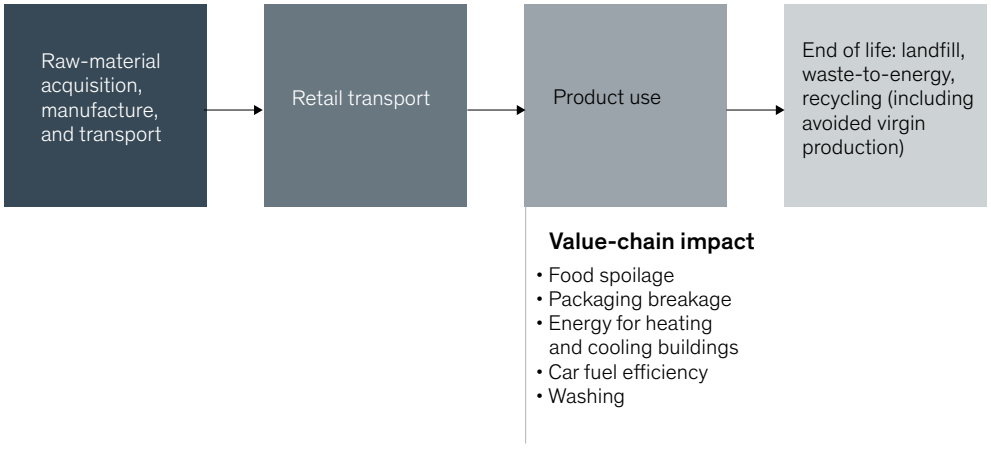
— *System boundary:* The analysis covers total GHG contributions, which includes both cradle-to-grave emissions as well as product-use impact versus alternatives. The system boundary in this paper is cradle to grave (throughout the product's life cycle), with the following phases (Exhibit 3):

  • Production: This includes resource extraction, raw-material processing, final product manufacturing, and all transportation steps.

Exhibit 3

We assessed the total greenhouse gas contribution of applications throughout the product's life cycle, including its value-chain impact.

Product life cycle



[9] *World energy outlook 2021*, International Energy Agency (IEA), October 2021; *What a waste 2.0: A global snapshot of solid waste management to 2050*, World Bank Group, 2018.
[10] For more on WARM, see "Waste Reduction Model (WARM)," US Environmental Protection Agency, accessed May 16, 2022.
[11] For more on ecoinvent, see "ecoinvent," accessed May 16, 2022.

- Retail transport: Retail transport emissions are calculated using the average number of miles traveled and the mode-specific fuel used based on product information obtained from the 2012 US Census Commodity Flow Survey.[12]

- Product use: We considered GHG emissions from the product use phase—including breakage, spoilage, heating or cooling requirements from improved insulation, and fuel efficiency from lightweighting—particularly where there are significant differences between plastics and alternative materials. Although our list is not exhaustive, we attempted to include significant sources of GHG emissions from the use phase to ensure a fair comparison.

- End-of-life disposition: We considered four end-of-life pathways via a consequential approach. We then adopted those pathways in our model in proportions that represent the share in the United States:

  - » landfill, including transport to landfill, methane emissions, and avoided utility emissions from energy recovery of methane

  - » waste-to-energy (WtE), which refers to incineration with energy recovery and includes transport to combustion site, GHG emissions from combustion, avoided utility emissions, and steel recovery offsets

  - » recycling, which includes collection, sorting, processing, and transport to a manufacturing facility that uses recycled inputs

  - » reuse, which includes collection, washing, and transport to the refilling facility

— *Calculation methods:* We built our models for direct and indirect impacts for each of the applications using the following rules and data sources.

- For calculation rules, we used the following conventions:

  - » We used Intergovernmental Panel on Climate Change (IPCC) characterization factors to normalize GHG emissions as kilograms of carbon dioxide equivalent (kg CO_2e). We used the 100-year global warming potential (GWP) to measure the warming effects of greenhouse gases.[13]

  - » We included methane and nitrous oxide (N_2O) from landfill or WtE of biogenic carbon, as well as cellulose in landfill storage (carbon sink).

  - » We excluded stored biogenic and fossil-derived product carbon, biogenic CO_2 from landfill or WtE, and stored carbon in fossil-derived products in landfills.

- For allocation rules, we used the following conventions:

  - » We allocated coproduct emissions based on the best consideration of material chemistry and production context, typically by mass.

[12] For more, see "Transportation—Commodity Flow Survey: United States: 2012," US Census Bureau, February 2015.
[13] L.A. Meyer and R.K. Pachauri (eds.), *Climate change 2014: Synthesis report*, Intergovernmental Panel on Climate Change (IPCC), 2014.

» We adopted the substitution approach as our recycling methodology in our life cycle approach, which offsets the production of virgin material and results in a net credit at end of life.

— *Data sources:* We leveraged the US Environmental Protection Agency's (EPA's) *Advancing sustainable materials management* report,[14] various industry reports, and McKinsey models for end-of-life disposition mix. The grid carbon factor was calculated based on the US Energy Information Administration's Annual Energy Outlook[15] and the EPA's Inventory of US Greenhouse Gas Emissions and Sinks[16] and Emissions & Generation Resource Integrated Database (eGRID). In addition, we leveraged data from the International Energy Agency (IEA) and the McKinsey Center for Future Mobility for regional energy mix and commercial-vehicle internal combustion engine (ICE) versus battery electric vehicle (BEV) mix for transportation of goods, respectively.

— *Indirect value-chain impacts:* We leveraged expert interviews and industry reports to identify secondary emissions during the use phase (such as breakage, fuel efficiency, and heating). For each indirect impact, we developed a calculation method and pressure tested it with industry experts.

Sensitivity analyses for select applications

To augment our US 2020 view, we performed sensitivity analyses to extend our GHG assessment to other regions, such as Western Europe and China, and to a decarbonized, circular world in 2050 for two illustrative applications: soft drink containers and milk containers. We based our sensitivity analyses on three main drivers: the energy mix, the end-of-life disposition mix, and the BEV versus ICE commercial-vehicle mix. We determined the energy mix of our base and best-case scenarios using IEA's Stated Policies Scenario (STEPS) and Sustainable Development Scenario (SDS), respectively.[17] The end-of-life disposition and BEV versus ICE mix for both cases were based on McKinsey models and expert interviews.

[14] *Advancing sustainable materials management: 2018 tables and figures*, US Environmental Protection Agency, 2020.
[15] *Annual energy outlook 2022*, US Energy Information Administration, March 2022.
[16] "Inventory of U.S. greenhouse gas emissions and sinks," US Environmental Protection Agency, updated April 14, 2022.
[17] For more, see "Stated Policies Scenario (STEPS)," World Energy Model, IEA, 2021; and "Sustainable Development Scenario (SDS)," World Energy Model, IEA, 2021.

4. Overall findings: Plastics have lower total greenhouse gas contribution in almost all cases examined

Plastic solutions provided lower GHG emissions in 13 of the 14 applications where plastic was compared with alternative materials. Furthermore, in cases where plastic was compared with plastic-enabled mixed materials, the plastic and mixed-material solutions had similar GHG profiles.

In the 13 applications for which plastic has lower emissions, the benefit was 10 to 90 percent lower GHG emissions than the next-best alternatives (Exhibit 4). This included indirect value-chain impacts, such as fuel savings in lighter cars, lower energy consumption in houses insulated with polyurethane, and reduced food spoilage when using plastic packaging instead of butcher paper.

If we exclude the indirect impacts and only compare direct life cycle emissions (production, retail transport, and end-of-life disposition), plastics have the lowest GHG impact in nine out of 14 applications. Depending on the application, this is generally due to one of two factors: (1) plastic is less energy intensive to produce;

Exhibit 4

Plastics have a lower greenhouse gas impact in 13 of the 14 nonplastic alternative applications analyzed, including both direct and indirect value-chain emissions.

			% difference in total greenhouse gas contribution in United States, 2020[1]		
Comparison	**Sector**	**Application**	*Plastic vs*	*Next-best alternative*	
Plastics vs alternative materials	Packaging	Grocery bag	HDPE[3]	Paper	80
		Wet pet food packaging	PET/PP[4]	Aluminum or steel	70
		Soft drink container	PET	Aluminum	50
		Fresh-meat packaging	EPS/PVC[5]	Paper	35
		Industrial drum	HDPE	Steel	–30
		Soap container	HDPE	Glass	15
	Building and construction	Municipal sewer pipe	PVC	Concrete or ductile iron	35–45
		Residential water pipe	PEX[6]	Copper	25
		Insulation	PU[7]	Fiberglass	80
	Consumer goods	Furniture	PP	Wood	50
	Automotive	Hybrid fuel tank	HDPE	Steel	90
		BEV[2] battery top enclosure	PP/glass fiber	Steel	10
	Textiles	Carpet	PET/nylon	Wool	80
		T-shirt	PET	Cotton	15
Plastics vs plastics-enabled mixed materials	Packaging	Milk container	HDPE	Paper	–5
	Consumer goods	Water cup	EPS	Paper	0

[1] Emissions include indirect impacts. [2] Battery electric vehicle. [3] High-density polyethylene. [4] PET is polyethylene terephthalate; PP is polypropylene. [5] Expanded polystyrene/polyvinyl chloride. [6] Cross-linked polyethylene. [7] Polyurethane.

for example, polyethylene terephthalate (PET) versus aluminum net of recycling rates, or (2) plastic is more weight-efficient (such as PET versus glass).

Indirect value-chain impacts can be substantial. In both insulation and hybrid-vehicle fuel tanks, the indirect impact far outweighs the direct impact. In the former, polyurethane insulates better than glass fiber batt and thus reduces heating fuel consumption, while in the latter, plastic tanks reduce vehicle weights and thus improve fuel efficiency. These indirect impacts offset plastics' generation of more GHG emissions than the nonplastic alternative in the production and disposal phases. This is not universal, however. The indirect impact in many applications is nonmaterial. For example, the indirect impact of decreased breakage in plastic bottles versus aluminum cans or glass bottles is insignificant.

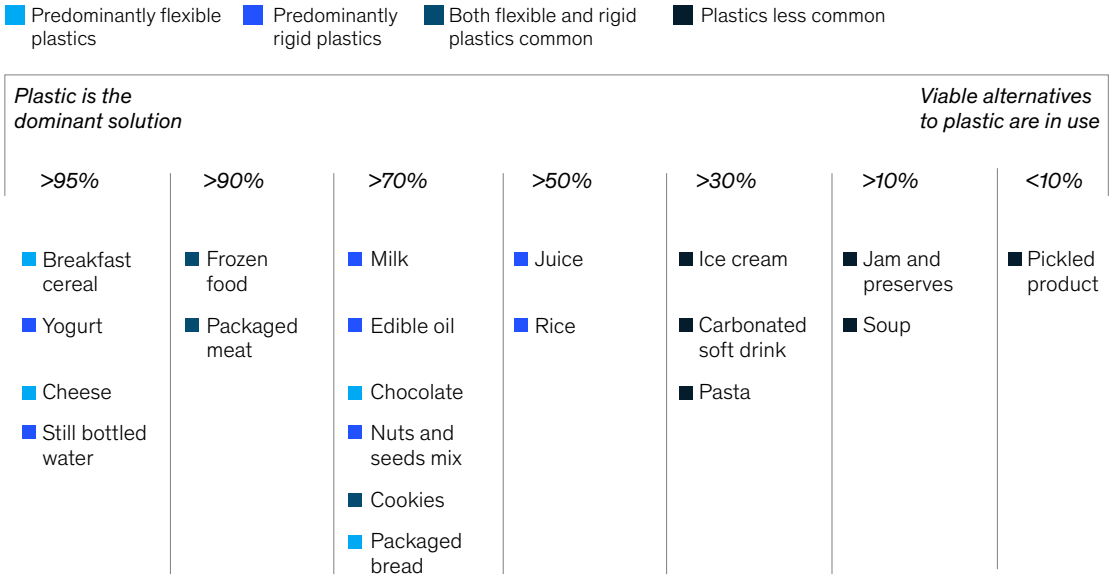
There are few at-scale alternatives to plastic in food packaging across a broad range of applications, driven primarily by reduced food spoilage when using plastics (Exhibit 5). An evaluation of 20 common food categories reveals that plastic packaging is used in more than 90 percent of products sold in six categories, including fresh and frozen meat. In another eight categories, plastic is present in the packaging of more than 50 percent of products sold. These figures translate to a significant but unquantified GHG benefit from plastics.

The drivers of lower GHG emissions vary by application. In industrial drums, steel wins on durability and recycling, resulting in nonplastic outperforming plastic for GHG emissions. While a steel drum produces

Exhibit 5

For the majority of food packaging applications, there are few viable alternatives to plastics.

Products with plastic packaging[1]



[1] Percentage reflects the fraction of products in which plastic is a component of the packaging.
Source: Euromonitor 2021, for USA 2021 full-year estimated sales

significantly more GHG emissions than a plastic drum during production, it lasts twice as long and is typically recycled. The performance driver is weight in the two applications where emissions are relatively equal—milk containers and drinking cups—because the nonplastic alternatives weigh approximately the same, equalizing emissions related to raw materials and transportation. Alternatively, in the application of grocery bags, paper bags weigh significantly more than HDPE bags. Consequently, they have much higher GHG emissions due to their production and transportation-related emissions. It is perhaps not surprising that materials that are more durable, lighter, or have higher recycling rates generate lower total GHG contribution. The trick is to know how much these positives outweigh the negatives, which we explore in more depth in the following section.

5. Selected examples: Soft drink containers, milk containers, and building insulation

To further illustrate how our analysis was carried out, we will discuss three applications in depth.

Soft drink containers

We began our deep dive with an application most people are familiar with: soft drink containers. The majority of soft drinks today are packaged in PET bottles, aluminum cans, or glass bottles. We based our analysis on 20-ounce PET bottles, 12-ounce aluminum cans, and 12-ounce glass bottles, which account for 17.0, 60.0, and 0.3 percent of the carbonated soft drink market in the United States, respectively. These specific sizes were selected because they represent the most common beverage container sizes for their respective material substrates. Comparing a 20-ounce PET bottle with a 12-ounce aluminum can favors the PET bottle because the material-to-volume ratio is significantly higher for smaller containers. In other words, it would require more plastic to distribute 100,000 fluid ounces of soda in 12-ounce PET bottles than in 20-ounce PET bottles, which would increase the GHG emissions. However, these sizes represent what consumers typically choose to purchase.

PET bottles have the lowest emissions because of their lightweight properties and the low amount of energy required to produce them.[18] By contrast, aluminum cans have two times the emissions of PET bottles, and emissions from glass bottles are three times higher. Although the PET bottle has the lowest production emissions, it has the least favorable GHG emissions for its end-of-life disposition (Exhibit 6). PET has the lowest recycling rate and credits from avoided virgin production among these three materials. It also has the highest emissions from WtE. (PET releases CO_2 when burned, whereas aluminum and glass do not.) However, the GHG impact of production emissions is more significant than end-of-life disposition emissions, resulting in PET having the lowest GHG impact.

The value-chain impact for soft drink containers is relatively small. The average shelf life is approximately 13 weeks for PET bottles versus 52 weeks for aluminum cans and glass bottles. PET bottles also have slightly higher spoilage rates (loss of carbonation) than aluminum and glass. That said, glass bottles break more easily than PET and aluminum. In both cases, additional GHG emissions are incurred from soft drink and bottle production to compensate for incremental spoilage and breakage of PET and glass bottles. However, in neither case is the total GHG contribution the result of incremental spoilage or breakage of materials.

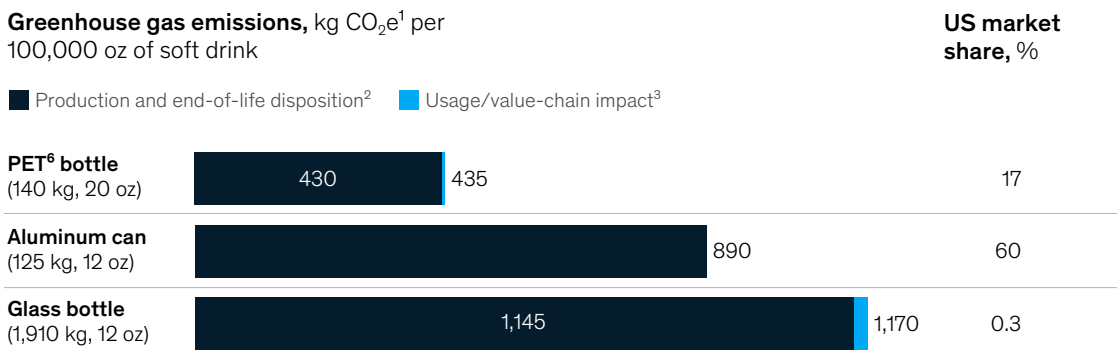
Milk containers

In the United States, refrigerated dairy milk is primarily sold in HDPE bottles and gable-top cartons, which are composed of 80 percent paper and 20 percent low-density polyethylene (LDPE). Sixty-four-ounce HDPE milk bottles have a market share of approximately 75 percent in the United States, while gable-top cartons account for around 25 percent.[19] This analysis is distinct from most other analyses in this study in that it is a comparison between plastics and plastics-enabled mixed materials. Paper without a layer of LDPE would not be able to contain the milk, highlighting the importance of LDPE even though it constitutes only 20 percent of the carton weight.

[18] This result is in line with published literature. See *Life cycle inventory of three single-serving soft drink containers*, Franklin Associates, August 2009.
[19] "Packaging in the US," Euromonitor, November 2021.

Exhibit 6

Soft drink container US 2020 view: PET bottle has the lowest total greenhouse gas contribution.



Note: Figures may not sum to 100%, because of rounding.
[1] CO_2 equivalent. [2] Includes raw-material acquisition, manufacture and transport, retail transport, and end-of-life disposition (ie, landfill, waste-to-energy, recycling, reuse); adopt end-of-life recycling method to allocate recycling credits. [3] Accounts for additional production of container and soft drink required to compensate for spoilage or breakage. [4] Waste-to-energy. [5] Includes waste volume sent to waste-to-energy facilities for aluminum cans and glass bottles. [6] Polyethylene terephthalate.
Source: US Environmental Protection Agency waste reduction model; McKinsey analysis

There are two primary packaging types for milk cartons (rather than milk bottles). The more common version is the previously mentioned gable-top carton, which stores pasteurized milk and requires refrigeration. The other type is an aseptic (or shelf-stable) carton that stores ultrahigh-temperature (UHT) pasteurized milk and does not require refrigeration. In the United States, aseptic "brick" cartons have less than 0.2 percent of the market share. We compared HDPE bottles with gable-top cartons in line with our general approach of analyzing products with a high market share. The expectation was that shelf-stable milk cartons would have considerably lower GHG emissions than gable-top cartons because they do not require a cold supply chain and refrigeration before use.

However, our analysis shows gable-top cartons have only a slightly lower GHG impact than HDPE bottles in the United States (Exhibit 7). While gable-top cartons emit around one-third less GHG than HDPE bottles during the production phase, end-of-life disposition emissions narrow the difference. Gable-top cartons contain paper that generates methane when landfilled, and this paper is not recycled at scale in the United States. HDPE bottles have significant recycling rates (around 30 percent), which, despite higher emissions when incinerated, generate a lower GHG impact at end of life.

Building insulation

Our assessment of the GHG impact of building insulation was done in the context of residential in-wall insulation for new builds. Our research shows the market share in the United States varies by region, but on average, fiberglass batt represents 60 to 70 percent of the market, with spray polyurethane foam (SPF) making up the second-largest share (20 to 30 percent). The remaining insulation types include foam boards (expanded polystyrene or polyisocyanurate), which are mostly used as continuous wall insulation, mineral wool, and blown cellulose, which is more commonly used for renovation than for new builds.

We based our analysis on a recent LCA with energy-modeling analysis published by the Spray Polyurethane Foam Alliance (SPFA)[20] that analyzed external wall insulation requirements for a 2,512-square-foot,

[20] *SPF residential energy modeling analysis*, Spray Polyurethane Foam Alliance (SPFA), February 2021.

Exhibit 7

Plastic milk bottles and gable-top cartons have similar shelf lives and total greenhouse gas contribution.

[1] CO_2 equivalent. [2] Includes raw-material acquisition, manufacture and transport, retail transport, and end-of-life disposition (ie, landfill, waste-to-energy, recycling, reuse); adopt end-of-life recycling method to allocate recycling credits. [3] Waste-to-energy. [4] Shelf-stable "brick" cartons represent <0.2% of market share; glass bottles represent <0.3% (Euromonitor). [5] High-density polyethylene. [6] Not shelf-stable; requires refrigeration.
Source: Carton Council of Canada; ecoinvent; Euromonitor International; Institut für Energie und Umweltforschung Heidelberg; thinkstep; US Environmental Protection Agency Waste Reduction Model; Waste and Resources Action Programme (WRAP)

two-story wood frame house in Richmond, Virginia. This region was selected because it represents a median US climate zone (International Energy Conservation Code climate zones in the US mainland range from 1 to 8; Richmond is in zone 4). To reach the building code standard of R-20 for external walls in Richmond, 360 kilograms (kg) of fiberglass batts and 330 kg of open-cell SPF are required.

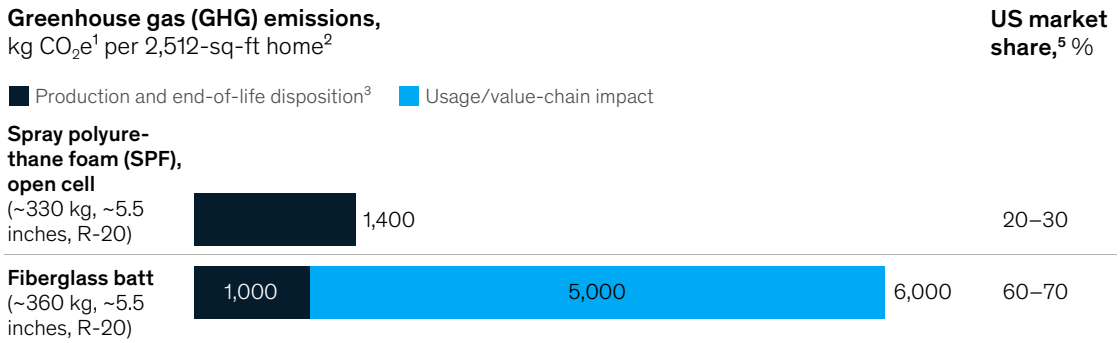
The main driver of GHG emissions comes from the use phase and is driven by the fact that fiberglass is permeable to air while SPF is not. The permeability of fiberglass also allows for greater heat transfer, which requires more heating and cooling throughout the insulation's lifetime of 75 years.[21] The overall result is that while SPF has a higher initial GHG impact in production, its incremental GHG savings from the use phase leads to approximately 80 percent lower GHG impact across the insulation lifetime when compared with fiberglass batt (Exhibit 8).

Our analysis shows gable-top cartons have only a slightly lower GHG impact than HDPE bottles in the United States.

[21] Building insulation service life is assumed to be 75 years, according to the North American Product Category Rules (PCRs).

Exhibit 8

Spray polyurethane foam has the lowest total greenhouse gas contribution despite its higher production emissions because of its air impermeability.



[1] CO_2 equivalent. [2] Functional unit defined as insulation required on 2-by-6-inch external walls (5.5-inch cavity) on a 2,512-square-foot, two-story wood-frame single-family detached home in Richmond, Virginia, per Spray Polyurethane Foam Alliance (SPFA) 2021 life cycle assessment (LCA) study; insulated in compliance with regional standards: attic (R-49) and walls (R-20), gas-fired air furnace and air conditioning, and gas-fired water heater. [3] Includes raw-material acquisition, manufacture and transport, retail transport, and end-of-life disposition (ie, landfill, waste-to-energy, recycling, reuse); adopt end-of-life recycling method to allocate recycling credits. [4] Waste-to-energy. [5] US insulation market share for new residential single-family homes (approximate numbers given large regional variation): 60–70% fiberglass, 20–30% SPF, ~10% other. [6] Fiberglass batts are air permeable, allowing for air infiltration and decreasing insulation properties.
Source: Carlisle Company; Colorado Department of Energy; ecoinvent; National Institute of Standards and Technology; Spray Polyurethane Foam Alliance (SPFA); US Census Bureau; US Energy Information Administration; US Environmental Protection Agency Waste Reduction Model; McKinsey analysis

6. Broad set of examples examined

In addition to soft drink containers, milk containers, and building insulation, we analyzed 13 other applications: five in packaging, two in building and construction, two in consumer goods, two in automotive, and two in textiles. Each application is representative of its respective sector's subcategory—for example, wet pet food and meat packaging for flexible food packaging, and water cups for consumer nondurable goods. We also included water cups within these 13 applications as a further example of plastics versus plastics-enabled mixed materials. We focused on the US 2020 perspective for these analyses because it is a reasonable proxy for the global average. Finally, the EPA's *Advancing sustainable materials management* report and interviews with experts informed end-of-life disposition rates.[22]

Grocery bags

A typical paper grocery bag has approximately 25 percent more carrying capacity[23] but is about six times heavier than a typical HDPE bag (55 grams versus eight). As a result, paper grocery bags have three times the production emissions of HDPE bags due to higher raw-material usage and transportation emissions. The difference in GHG impact between HDPE and paper bags widens further to five times when accounting for end-of-life disposition and impact in use (such as "double bagging"). In the United States, where landfill is more common than WtE (80 versus 20 percent), a properly landfilled HDPE bag has a more favorable end-of-life GHG impact than paper because landfilling paper results in extensive methane emissions from anaerobic decomposition. This work does not consider open-water dumping as an end-of-life scenario for grocery bags because it is focused on the United States, which has a developed waste management system with minimal leakage into the environment. However, this is not the case in countries with incomplete waste management systems, where significant leakage is one of the major contributors to ocean pollution. This leakage will need to be tackled in the future by improving and optimizing global waste management to minimize pollution. The impact of properly regulated landfilling outweighs the GHG benefits of recycling (paper bags have recycling rates of 21 percent versus 8 percent for HDPE bags) and WtE (carbon emissions from paper combustion are considered biogenic). On average, 20 percent of plastic bags and 50 percent of paper bags are double bagged to compensate for breakage and leakage, resulting in a comparatively higher value-chain GHG impact for paper bags.

Wet pet food containers

The wet pet food market is primarily dominated by plastic and metal packaging. Flexible multilayer pouches—which are made up of polypropylene (PP) (75 percent), aluminum foil (20 percent), and PET (5 percent)—constitute approximately 30 percent of the US market. Metal cans are split between aluminum (45 percent market share) and steel cans (roughly 15 percent). Compared with plastic pouches that are not recyclable because of the mixed materials used to produce them, aluminum and steel cans have recycling rates of about 50 and 70 percent, respectively. Despite their higher recycling rate, metal cans tend to be heavier, with aluminum cans weighing 1.5 times as much as plastic multilayer pouches and steel cans five times as much, resulting in high production emissions. These high production emissions offset the credits from recycling for metal cans, with the result that GHG emissions are three times higher for cans than for plastic multilayer pouches.

[22] For more, see *Advancing sustainable materials management: 2018 tables and figures*, US Environmental Protection Agency, 2020.
[23] A paper grocery bag carries on average 7.43 items, while an HDPE bag carries 5.88 items, per *Life cycle assessment of supermarket carrier bags: A review of the bags available in 2006*, Environment Agency, United Kingdom, 2011.

Fresh-meat packaging

In the United States, the two most common fresh-meat packaging options are expanded polystyrene (EPS) foam trays with polyvinyl chloride (PVC) film and butcher paper. We chose pork as a representative meat for attributing GHG emissions to food spoilage because it is less GHG intensive than beef and lamb but more so than chicken, providing a representative example across meat products. EPS foam trays are closed-cell with absorbent pads. Although EPS foam trays with PVC film have higher production emissions than butcher paper, their lower rates of spoilage for pork compared with butcher paper (approximately 5 versus 7 to 10 percent) more than make up the difference. As a result, the EPS and PVC packaging has lower overall GHG impact than butcher paper by about 35 percent. In addition, because the packaging used for fresh meat often ends up as landfill in the United States, plastics has an advantage over paper because of methane emissions from the anaerobic decomposition of paper.

Hand soap bottles

Our analysis of hand soap bottles shows the GHG benefits of reuse. Refilling a glass bottle 15 to 20 times with flexible PP pouches results in approximately 25 percent lower GHG emissions than using 15 to 20 HDPE hand soap bottles. These figures are driven by lower production emissions for flexible PP refilling pouches than for rigid HDPE bottles, even after accounting for soap wastage from refilling, such as accidental spillage of soap during transfer. That said, reusing HDPE bottles has the lowest GHG emissions, with 15 percent lower emissions than reusing glass bottles.

Industrial drums

The relative GHG performance of HDPE versus steel drums depends on differences in production emissions, durability, and recycling rates. A single steel drum has higher production GHG emissions than a single HDPE drum. However, for the defined functional unit of ten years, the higher durability of steel drums, which have a ten-year lifespan, compared with that of HDPE drums, which have a five-year lifespan, negates the difference in per-drum production emissions. Furthermore, steel drums have a higher recycling rate (80 percent) than HDPE drums (20 percent) and more favorable recycling credits from avoided virgin production—factors that ultimately tip the balance in favor of steel drums, even after accounting for the higher levels of maintenance required to fix dents in steel drums. Overall, using a single steel drum instead of two HDPE drums over ten years results in approximately 30 percent net GHG savings.

Municipal sewer pipes

There are two main types of sewer pipes: gravity pipes (with approximately 90 percent of market share) and force main or pressure pipes (about 10 percent). PVC and reinforced concrete are the most common materials used in gravity pipes, while PVC and ductile iron are most prevalent in force main pipes. To ensure a fair comparison, we based our assessment on pipe specifications that are most comparable.[24] We assumed all four pipes have a designated service life of 100 years. In both sewer pipe applications, PVC has lower GHG emissions (approximately 45 percent lower than reinforced concrete and 35 percent lower than ductile iron), primarily because of its ability to achieve the same function with lighter weight. Concrete and ductile pipes also require more GHG-intensive transport and installation processes. It is noteworthy that ductile-iron pipes have comparatively higher recycling rates (about 30 percent) than PVC pipes (about 10 percent). We have not been able to quantify pumping efficiency for force main pipes, but it favors PVC, which is already the material with lower GHG impact.

[24] 15-inch sewer gravity main pipe: PVC (ASTM D3034, SDR 26) versus reinforced concrete (ASTM C76, Wall B); 12-inch sewer force main pipe: PVC (ASTM D2241, SDR 21) versus ductile iron (AWWA C151).

Residential water pipes

Copper type L and cross-linked polyethylene (PEX) pipes are two common examples of residential water pipes. The most important factor when comparing the GHG emissions of copper versus PEX pipes is that copper has a higher thermal conductivity than plastic. We estimate that GHG emissions from incremental heat loss are about 35 percent higher in copper pipes than PEX pipes in a 2,811-square-foot home with most water use for a family of four concentrated in the mornings and evenings. Copper pipes also have about 2.5 times the production emissions of PEX pipes because of their heavier weight and more energy-intensive production process. However, the difference in production emissions is dwarfed by the difference in incremental heat loss. Although copper is highly recyclable, its potential is not fully captured because small-scale residential demolition contractors often do not sort copper pipes for recycling. Hence, the US recycling rate is estimated at only 30 percent. By contrast, PEX pipes are rarely recycled. Overall, PEX pipe has about 25 percent lower total GHG emissions than copper pipes.

Furniture

We modeled furniture as a representative example of consumer durable goods and defined the functional unit as a set of one square table and four chairs with a life span of ten years. For this analysis, we assessed the GHG impact of three common furniture materials: PP, wood, and steel. The PP furniture set has the lowest GHG emissions, primarily because it can provide similar performance and functionality using less material (around 20 kg for PP versus 40 kg each for wood and steel), which reduces the emissions associated with raw-material acquisition, manufacturing, and transport.

Hybrid fuel tank

For hybrid-vehicle automotive applications, most of the GHG impact stems from impact in use. We defined the functional unit as a fuel tank for a midsize hybrid sedan in the United States with a lifetime mileage of 200,000 miles and compared HDPE and steel fuel tanks. HDPE fuel tanks allow around 90 percent net GHG savings overall compared to steel, despite comparable direct GHG impact in production and end of life, primarily because their lighter weight leads to higher fuel efficiency. Our research shows that recycling rates for automotive steel in general, including fuel tanks, are about 95 percent, while rates for HDPE fuel tanks are comparatively lower at about 65 percent).

Automotive electric-vehicle battery pack top enclosures

In addition to looking at hybrid vehicle fuel tanks, we also selected battery pack top enclosures as a representative application in BEVs and as a comparison to hybrid fuel tanks. The two most common material types are fiberglass reinforced PP and steel. Similar to the hybrid-vehicle fuel tank application, the light weight of battery packs is a consideration in the use phase. Still, its importance is significantly diminished because BEVs are more energy efficient than hybrid vehicles, and the share of renewables or nuclear energy in the United States is sizable (around 40 percent of the total power mix).[25] Battery enclosures made of PP and fiberglass have about 10 percent lower GHG impact than steel enclosures over their lifetime mileage of 200,000 miles. That said, EVs have not yet reached end of life at scale, so our recycling rates are estimated based on expert interviews. PP-and-fiberglass enclosures emit less GHG emissions during production but will likely not be recycled, because their mixed-materials nature represents a recycling challenge. The lightweight nature of plastic battery housing enclosures also provides an opportunity to reduce battery size and avoid emissions associated with battery production.[26] Compared with plastic, steel enclosures are expected to have a high recycling rate of about 95 percent because they can be part of

[25] *World energy outlook*, 2021.

[26] Reduction in battery size is possible through BEV light-weighting if BEV can: (1) maintain minimum acceptable range of 250–300 miles, (2) achieve lightweighting at reasonable cost, and (3) achieve material weight reduction (at least 20 to 30 kilograms) and current BEV weight is at border of next test weight class.

existing automotive steel recycling flows. Still, they require more electricity consumption over their service life because of their heavier weight.

T-shirts

Apparel accounts for about 50 percent of the textile sector's total 11 MMT plastics volume. We selected T-shirts as a representative application, comparing the GHG impact of PET versus cotton T-shirts. Overall, PET T-shirts have a lower GHG footprint than cotton T-shirts, primarily because of lower production emissions. Cotton emits a considerable amount of GHG across the various stages of crop cultivation, such as crop rotation, use of fertilizer and pesticides, and irrigation. Additionally, T-shirts are generally not recycled, and the end-of-life disposition is split almost equally between WtE and landfill.

Carpet

Carpet is another major textile category, corresponding to approximately 1 MMT (or 10 percent) of total textile plastics volume. A majority (around 85 percent) of the carpet market is dominated by synthetic carpet (PET/nylon). The only nonplastic alternative is wool, which constitutes only 3 to 5 percent of the US market share and is primarily used in high-end carpets. Synthetic carpet emits five times less GHG emissions than wool carpet due to lower production emissions. Only about 5 percent of synthetic carpet is recycled in the United States, mainly in California. Further increases in carpet recycling would widen the GHG benefits of PET/nylon versus wool since wool carpet cannot be recycled.

Water cups

We assessed the GHG impact of three types of plastic cups (EPS, PET, and PP) and compared them with paper and reusable glass cups. The EPS cups had the lowest GHG emissions because they have the lowest weight and production emissions. Paper cups have similar GHG emissions to EPS cups because of their low production emissions and favorable WtE GHG impact (CO_2 from paper combustion is considered biogenic and hence excluded). It is important to note that paper cups contain approximately 5 percent LDPE by weight and are considered a plastics-enabled mixed material. Like gable-top milk cartons, the LDPE lining enables paper cups to hold liquids. Emissions from reusable glass cups are highly sensitive to the washing process, especially the choice of hot versus ambient-temperature water. We estimated that one glass cup can be reused up to 500 times and can be washed with hot water in a commercial dishwasher in batches of 50. Using hot water results in five times the GHG emissions compared with using ambient water because of the use of industrial gas boilers, which have a relatively high GHG footprint. Reusable glass cups that are washed with ambient water have a lower GHG impact than both EPS and paper cups.

7. Sensitivities and opportunities to reduce GHG impact across materials

We performed sensitivity analyses to extend our GHG assessment to other regions, such as Western Europe and China, and created a view of a decarbonized, circular world in 2050. We relied on three main drivers: the energy mix, the end-of-life disposition mix, and the BEV versus ICE commercial-vehicle mix for transportation of plastics and plastic alternatives. The energy mix affects process energy, while the BEV versus ICE vehicle mix affects transport energy. Process non-energy emissions (such as from catalysts or water use) are assumed to be constant. This streamlined approach offers a high-level perspective of regional nuances and a view of 2050 to help identify significant abatement levers for each product analyzed. Finally, this analysis focuses on soft drink containers and milk containers.

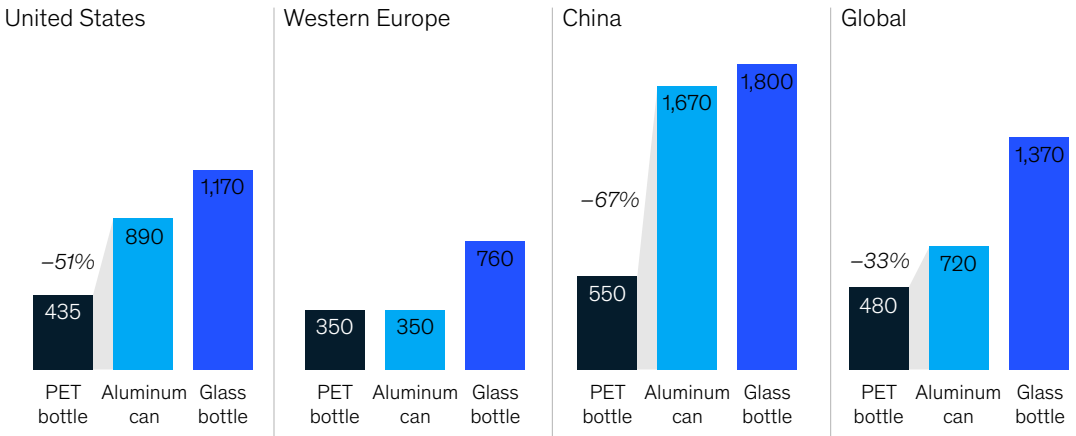
Soft drink containers

The relative performance of PET, aluminum, and glass varies by region. Although PET bottles have the lowest GHG emissions in the United States, aluminum cans have lower GHG emissions in Western Europe, while glass bottles still have the highest emissions everywhere (Exhibit 9). This is because Western Europe has a cleaner energy mix and higher recycling rates for aluminum cans. Aluminum production uses a high

Exhibit 9

Aluminum cans are competitive with plastic bottles in Western Europe but have higher total greenhouse gas contribution footprints in China.

2020 greenhouse gas (GHG) impact, kg CO_2e[1] per 100,000 oz of soft drink



Aluminum cans and glass bottles are more energy intensive to produce and hence more sensitive to energy mix than polyethylene terephthalate (PET) bottles

Aluminum cans are comparable to PET bottles in Western Europe due to cleaner energy mix and higher recycling rate

Higher recycling rates of PET and aluminum do not sufficiently compensate for a coal-heavy energy mix in China, resulting in correspondingly higher emissions than in United States

Global energy mix and recycling rates resemble those of United States, resulting in similar GHG trend

[1] CO_2 equivalent.
Source: McKinsey analysis

share of hydropower in the United States and Western Europe and relies mostly on coal in China. Western Europe imports about 50 percent of its aluminum ingots from Iceland, Mozambique, Norway, the United Arab Emirates, and others, suggesting the true GHG impact may be higher than calculated. By contrast, China has the highest overall emissions for all materials because of its coal-heavy energy mix. In China, higher recycling rates of PET bottles and aluminum cans do not sufficiently compensate for a coal-heavy energy mix.

In our 2050 base case, a cleaner energy mix, higher recycling rates, and greater commercial BEV penetration reduce the overall emissions of the three materials. Because of the energy-intensive nature of production, both aluminum and glass benefit disproportionally from decarbonizing the electric grid (Exhibit 10). Moreover, because PET emissions in 2050 will be primarily driven by emissions from WtE and since its production process is less energy intensive, PET emissions will decrease relatively slowly compared with aluminum and glass, leading to a narrowing of PET's GHG advantage. In fact, under the 2050 best-case scenario (a 1.5° pathway), aluminum cans have lower GHG emissions than PET bottles.

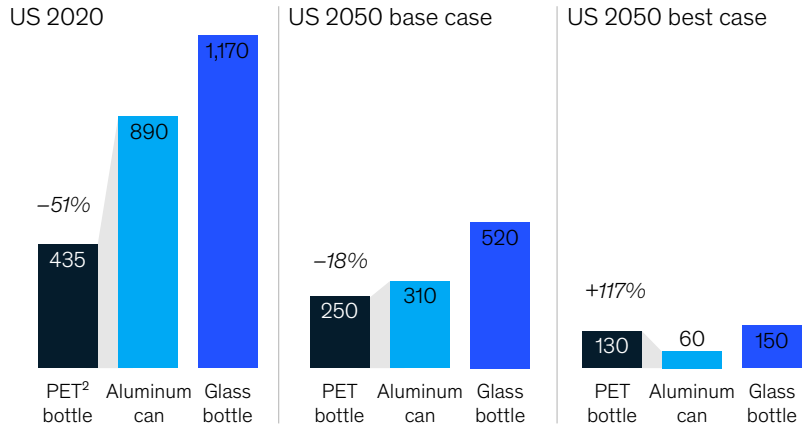
Milk containers

In all regions investigated, gable-top cartons are the lower-GHG alternative to HDPE bottles because of their higher rates of recycling or WtE versus landfill mix (Exhibit 11). This is in line with findings from published reports that show gable-top cartons have lower GHG emissions than HDPE bottles in Europe,[27] Australia, and New Zealand.[28] That said, the energy mix has similar overall effects on both HDPE bottles and

Exhibit 10

Aluminum and glass will benefit disproportionally from decarbonizing the electric grid.

Greenhouse gas impact, kg CO_2e[1] per 100,000 oz of soft drink



[1] CO_2 equivalent.
[2] Polyethylene terephthalate.
Source: McKinsey analysis

[27] *Comparative life cycle assessment of Tetra Pak carton packages and alternative packaging systems for beverages and liquid food on the European market*, Institute for Energy and Environmental Research Heidelberg GmbH (ifeu), March 2020.
[28] *LCA of beverage and food packaging in Australia and New Zealand*, thinkstep-anz, January 2021.

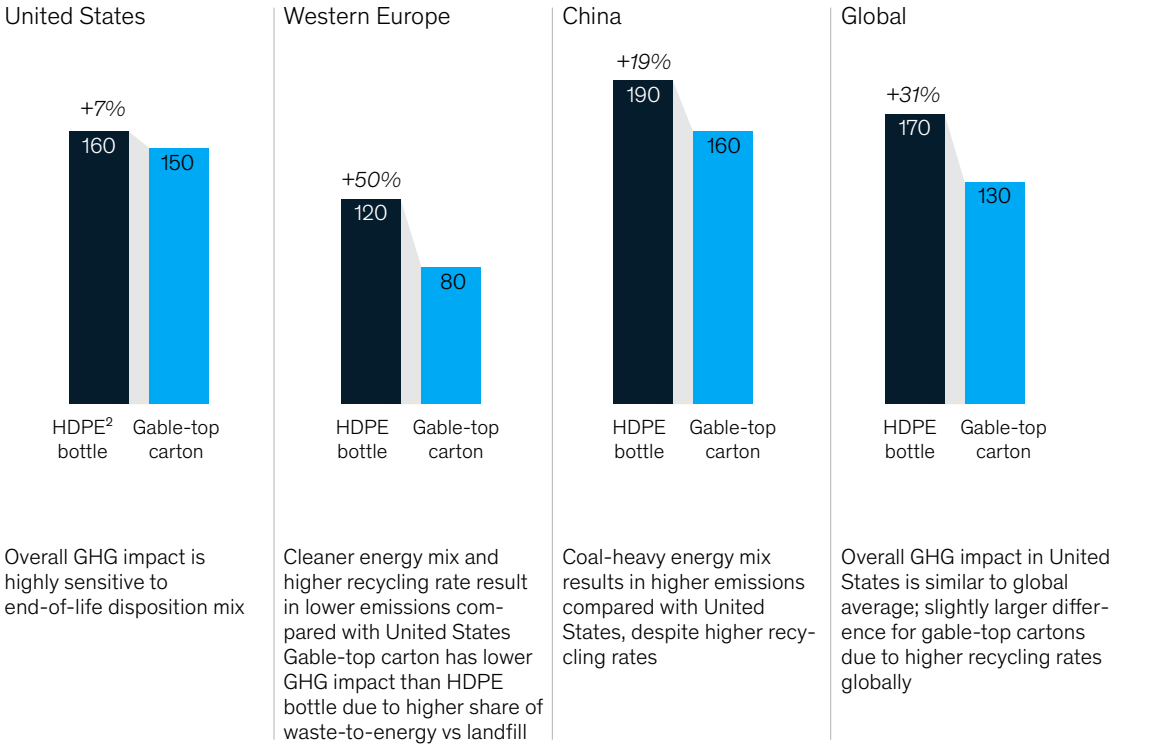
gable-top cartons, with lower overall emissions in Western Europe than in the United States and with higher emissions in China. However, HDPE milk bottles tend to be much less common outside the United States.

Decarbonizing the US energy mix by 2050 will significantly lower the GHG impact of both products. In the base case, for which there is an overall increase in WtE rates and a sizable increase in recycling rates for gable-top cartons, cartons outperform HDPE bottles. In the best-case scenario (100 percent renewable or nuclear energy and high recycling), both products generate low GHG emissions, but HDPE has a slightly lower GHG impact because of its higher recycling rates (Exhibit 12).

Exhibit 11

Gable-top cartons have lower impact than plastic bottles in Western Europe and China because of higher rates of recycling and waste-to-energy versus landfill mix.

2020 greenhouse gas (GHG) impact, g CO_2e[1] per 64 oz of refrigerated dairy milk

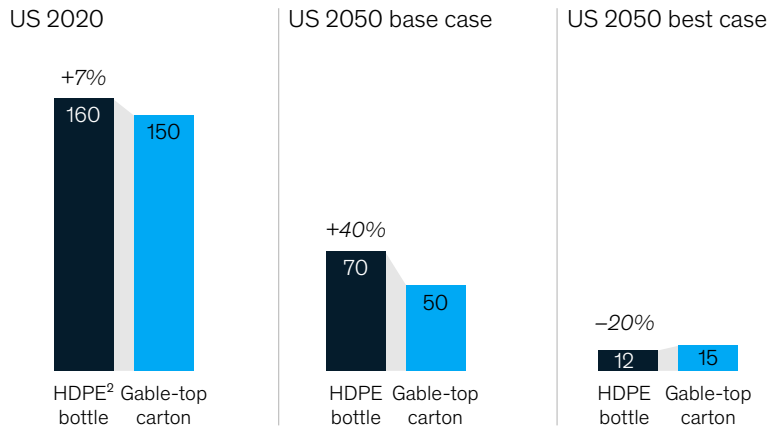


[1] CO_2 equivalent.
[2] High-density polyethylene.
Source: McKinsey analysis

Exhibit 12

In a decarbonized world, plastic bottles will have a slight advantage over gable-top cartons because of higher rates of recycling.

Greenhouse gas impact, kg CO_2e[1] per 100,000 oz of soft drink



[1] CO_2 equivalent.
[2] High-density polyethylene.
Source: McKinsey analysis

Potential for improvement

In a decarbonized, highly circular world (such as in our 1.5° pathway), GHG footprints for all materials will be improved by a cleaner energy mix, improved recycling rates, and higher commercial BEV penetration rates. However, the extent of GHG reduction varies by material. In general, materials that are energy intensive to produce, such as aluminum and glass, will benefit disproportionally from decarbonizing the grid and, to a lesser extent, from avoiding virgin production through recycling. The landfill versus WtE mix has a significant impact on materials that contain carbon, such as plastics and paper, but has a lower impact on other materials, such as aluminum, steel, and glass. Incinerating plastics for WtE has a net result of increasing GHG, because the emissions from combustion outweigh avoided utility emissions. Thus, a cleaner grid decreases the benefits of avoided utility emissions, increasing WtE penalties versus landfill for plastics. The opposite is true for paper: landfilling paper results in methane emissions from anaerobic decomposition (considered anthropogenic GHG and hence included), while incinerating paper for WtE has a negligible impact (CO_2 emissions from paper combustion are considered biogenic GHG and therefore excluded; N_2O emissions are considered anthropogenic GHG but have a small impact).

Our 2050 base and best-case scenarios represent two potential pathways. As previously mentioned, the relative GHG performance of different materials is sensitive to the energy and end-of-life disposition mixes, suggesting that each material has the potential to have the lowest GHG emissions under the right set of conditions (Exhibit 13). As a result, we have highlighted major levers that each material class can adopt to further reduce GHG emissions in the years to come.

Exhibit 13

Plastics, metals, glass, and paper all have the potential to further reduce emissions to help achieve net-zero-emissions goals.

Plastics

- Electrify and use renewable energy in manufacturing process
- Promote reuse
- Reduce waste-to-energy (eg, divert to recycling or landfill)
- Implement carbon capture and storage at waste-to-energy plants
- Increase recycling and recycled content and improve recycling yield

Metals

- Use renewable energy in manufacturing process
- Increase recycling and recycled content

Glass

- Use renewable energy in manufacturing process
- Promote reuse
- Implement more energy-efficient washing at reuse plants
- Increase recycling and recycled content

Paper

- Use renewable energy in manufacturing process
- Increase recycling and recycled content
- Implement methane capture and energy recovery at landfill sites

[1] Electrical accounts for 6.05 million metric tons, medical accounts for 5.14, and industrial accounts for 0.29.
Source: McKinsey Chemical Insights

David Feber is a senior partner in McKinsey's Detroit office, **Stefan Helmcke** is a senior partner in the Vienna office, **Thomas Hundertmark** is a senior partner in the Houston office, **Chris Musso** is a senior partner in the Denver office, **Wen Jie Ong** is a consultant in the Seattle office, **Jonas Oxgaard** is an associate partner in the New York office, and **Jeremy Wallach** is a partner in the Boston office.

An appendix with calculation inputs and assumptions is available upon request.

Critical review statement

by Miguel Brandão
May 12, 2022

The present statement reflects the iterative reviews made by Dr. Miguel Brandão and Dr. Jonathan Cullen on the life cycle assessment (LCA) study of plastics performed by McKinsey authors David Feber, Stefan Helmcke, Thomas Hundertmark, Chris Musso, Wen Jie Ong, Jonas Oxgaard, and Jeremy Wallach.[29] The LCA study reviewed consists of a streamlined cradle-to-grave LCA of 16 plastic applications, including indirect effects, limited to their greenhouse gas (GHG) emissions. Furthermore, results are compared with those of nonplastic alternatives. This critical review ensures that the study complies with the following:

— The methods used to carry out the LCA are scientifically and technically valid but not necessarily fully compliant with International Organization for Standardization (ISO) standards 14040, 14044, and 14067, nor with technical specifications (TS) 14071 because such a comprehensive study is outside the scope of the endeavor.[30]

— The data used are appropriate and consistent with the goal and scope of the study, and the interpretation is subject to the limitations identified.

— The report is transparent and internally consistent.

All these features represent the checks and balances that ensure the quality of the study and the validity of its results and interpretation. This statement was written after the study was concluded and is the result of the following seven-stage procedure:

1. Reviewers read and comment on the report.
2. Reviewers meet and agree on a review statement reflecting consensus among them.
3. Review chair writes a two-page review statement and sends more specific comments.
4. Study authors go through reviewers' comments and make a revised report and an itemized reply.
5. Review chair reads the authors' itemized reply and gives any remaining comments.
6. Authors go through any remaining issues the review chair might have and create a revised LCA report and itemized reply.
7. Review chair reads the authors' revised itemized reply and gives final approval or request for changes.

This statement and the associated review meet the following criteria:

— It corresponds to step seven above and pertains to the final version of the LCA study, which was sent on May 10, 2022.

[29] *Climate impact of plastics*, McKinsey, May 10, 2022, version (unpublished).
[30] "ISO 14040:2006: Environmental management – Life cycle assessment – Principles and framework," International Organization for Standardization (ISO), 2006; "ISO 14044:2006: Environmental management – Life cycle assessment – Requirements and guidelines," ISO, 2006; "ISO/TS 14067:2013: Greenhouse Gases – Carbon footprint of products – Requirements and guidelines for quantification and communication," ISO, 2013; "ISO/TS 14071:2014: Environmental management – Life cycle assessment – Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006," ISO, 2014.

— It includes a general assessment of the life cycle inventory (LCI) model and of the individual data sets.

— It covers all aspects of the LCA, including data appropriateness and reasonability, calculation procedures, LCI, impact assessment methodologies, characterization factors, calculated LCI and life cycle impact assessment (LCIA) results, and interpretation.

— It characterizes the study against a fixed set of criteria that are commonly used in LCA reviews. These characteristics cover each of the four phases of a LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation.

1. Goal and scope definition
This section of the study, although not explicitly stated in these terms, includes a description of the functional units, system boundaries, LCIA (including a focus on the climate-change impact category, as well as how biogenic carbon and methane were dealt with), allocation rules, and data sources (which were clearly specified). It is outside the scope of this review to address the goals chosen for the LCA study in question because it is impossible to either verify or validate them.

2. Life cycle inventory
This section describes the data and modeling in the reviewed LCA study. There is no specific section dedicated to it, but the main processes are characterized numerically in the appendix.

3. Life cycle impact assessment
A competent LCIA is applied, and its results, including a contribution analysis for climate change, are shown in terms of general hot spots.

4. Interpretation
The study includes a sensitivity analysis. Furthermore, limitations are identified. Results are discussed, as are reasons for the results. The conclusions extrapolated are robust and rest on the analysis reported that preceded it.

Conclusion
The review of the LCA study of plastics revealed a competent analysis. The insights derived are supported by the consistent and scientific application of the LCA methodology. As review chair, I therefore conclude that the study and the results are of good quality because authors have satisfactorily addressed the comments and concerns raised by the reviewers.

Miguel Brandão is an associate professor in industrial ecology and life cycle assessment in the Department of Sustainable Development, Environmental Science, and Engineering (SEED) at KTH Royal Institute of Technology. **Jonathan Cullen** is an associate professor in energy, transport, and urban infrastructure in the Resource Efficiency Collective, which is a part of the Department of Engineering at the University of Cambridge.

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