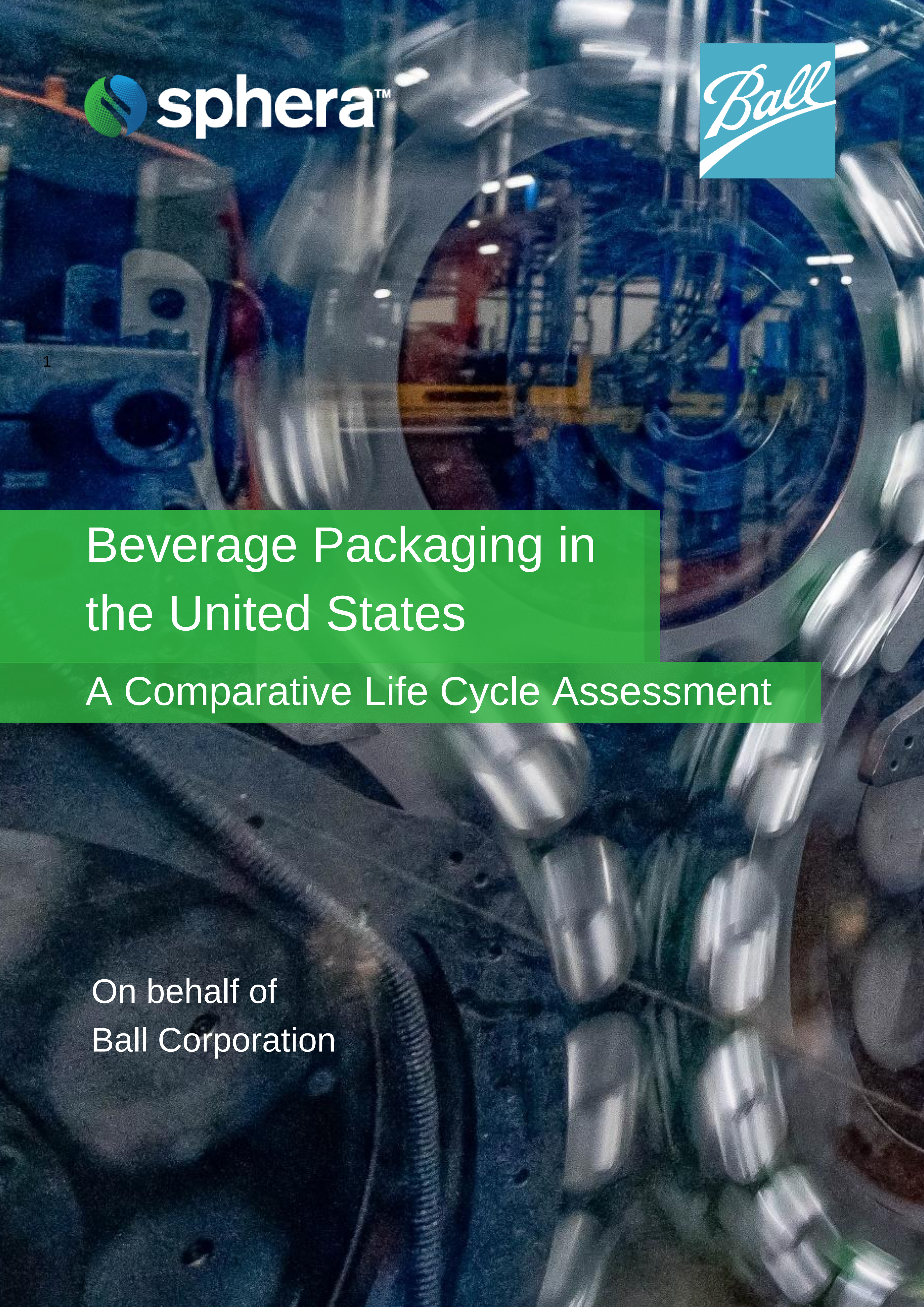


Beverage Packaging in the United States

A Comparative Life Cycle Assessment

On behalf of
Ball Corporation

Client: **Ball Corporation**

Title: **Beverage packaging in the United States (US) – A Comparative Life Cycle Assessment**

Report version: v3.0

Report date: 16/07/2020

On behalf of Sphera and its subsidiaries

Document prepared by

Flora D’Souza fdsouza@sphera.com

16.07.2020 phone +49-711-341817-406

Contributing authors

Rosie Dodd

Maike Horlacher

Iris Matzke

Quality assurance by

Manfred Russ Manfred Russ

Principal Consultant 16.07.2020

Under the supervision of

Dr Sabine Deimling

Principal, Team Lead Food, Agriculture and Renewable Materials

During the course of the project, thinkstep became Sphera Solutions GmbH. Therefore, all references to ‘thinkstep’ in this report refer to “Sphera Solutions”.

Disclaimer (Sphera):

This report has been prepared by Sphera with all reasonable skill and diligence within the terms and conditions of the contract between thinkstep and the client. Sphera is not accountable to the client, or any others, with respect to any matters outside the scope agreed upon for this project.

Regardless of report confidentiality, Sphera does not accept responsibility of whatsoever nature to any third parties to whom this report, or any part thereof, is made known. Any such party relies on the report at its own risk. Interpretations, analyses, or statements of any kind made by a third party and based on this report are beyond Sphera’s responsibility. If you have any suggestions, complaints, or any other feedback, please contact us at servicequality@sphera.com.

Disclaimer (Ball):

This Regional Summary is drawn from a comparative Life Cycle Assessment Report (“LCA”) conducted by Sphera at Ball Corporation’s request. Throughout the production of the LCA, Sphera had full control over the methodology used, the conclusions reached and the contents of LCA. Neither Ball Corporation, nor its employees, officers or directors makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information contained in this Regional Summary, or represents that its use would not infringe privately owned rights The findings and views expressed in this Regional Summary do not necessarily reflect the views of Ball Corporation.

1.1. Abstract

- A comparative Life Cycle Assessment (LCA) was commissioned by Ball Corporation to compare the environmental performance of single-use, small to medium-size aluminum cans and bottles against alternative beverage packaging, in three regions (EU; US and BR). While the full LCA report is available upon request from the commissioner, this regional summary report focuses only on the US. The Life Cycle Impact Assessment (LCIA) was complemented by calculations of the Material Circularity Indicator of each packaging option. A critical review was conducted by a panel of three independent experts to ensure conformity to ISO 14040/44 standards. The full report, from which this document is an extract, is available upon request.
- The primary intended application of the study is to provide up-to-date and objective results in various sustainability metrics of specific beverage packaging alternatives: aluminum cans and bottles, PET bottles, glass bottles and beverage cartons.
- A specific selection of 2-4 products per packaging material were purchased, measured and weighed. Ball Corporation supplied primary environmental data on can manufacturing, while all other background and foreground data were based on industry averages and association datasets from the GaBi Databases 2019. The full life cycle of the beverage packaging was modelled, excluding among other things the beverages themselves, using the cut-off approach. Note that other methodological approaches were chosen in the two other regions not shown in this summary report.
- While in general conservative assumptions have been taken with respect to the aluminum can to avoid unfair bias and misrepresentation, the data quality difference remains a potential limitation of the study.
- It was confirmed that packaging efficiency has a significant impact on the environmental burdens of the packaging, as a container with a larger volume requires relatively less material to provide a given quantity of product. Each packaging option has distinct advantages and disadvantages, with potential for improvement by changing the recycling rate, recycled content and product weight.
- Aluminum cans compete with PET bottles as the best performers among the packaging options for carbonated beverages, and rank second-to-third among packaging for non-carbonated beverages after PET and beverage cartons. PET bottles perform well due to being lightweight, requiring little secondary packaging, and having a relatively low manufacturing energy demand. The strong performance of the aluminum cans can largely be attributed to the lightweight nature of the product compared to other packaging types, the high recycled content (73%) and the decent recycling rate (when compared to other substrates) of 50% at end of life.
- Material circularity is measured and generally correlates well with findings for global warming potential, although this is not a causal relationship given material circularity does not measure material efficiency.
- The results vary from region to region and show slightly different rankings and conclusions (not explored here). Overall, there is not one single packaging material which outperforms all the alternative options in all selected impact categories. Each packaging option exhibits different environmental strengths and weaknesses.

1.2. Goal

The goal of the study is to conduct an LCA analyzing the environmental performance of single-use, small to medium-size aluminum cans and bottles compared to competing alternative beverage packages (i.e. PET bottles, glass bottles and beverage cartons). One focus of the study is explicitly on varying degrees of recycling rates and recycled content to understand interdependencies between circular product design and environmental impacts of different beverage packaging options.

The study has been commissioned by Ball Corporation and is intended to be disclosed to the public. This excludes confidential primary data. As the study includes comparative assertions of different beverage packaging systems, a panel of independent experts was assigned to carry out a critical review of the study.

The intended applications of the study are:

- to provide up-to-date and objective results of various sustainability metrics for specific beverage packaging alternatives;
- to provide a comprehensive overview of product sustainability and potential for overall improvement by complementing life cycle assessment results with the material circularity (MCI) methodology, a socio-economic metric;
- to apply the learnings of regional results to develop communication and/or product marketing strategy, and in the medium term, further optimize product design;
- to pinpoint the advantages and disadvantages of specific aluminum packaging types over alternatives, and to provide a benchmark among the most common single-use small-to-medium size beverage packaging alternatives in the US.

The reasons for carrying out the study include:

- to identify the environmental hotspots of the aluminum can’s life cycle and related optimization potential;
- to understand the environmental advantages/drawbacks of beverage cans and bottles in the specific context of the US;
- to compare the environmental impacts of various beverage packaging alternatives, with the intention of comparative assertions intended to be disclosed to the public (except for confidential primary data);
- to provide comparative environmental impact information to brands and other interested parties that may result in further market share growth of aluminum beverage cans;
- to inform and improve the commissioner’s corporate sustainability strategy.

The study is intended for publication, to beverage manufacturers as the primary audience, but also to provide credible communication material for retailers and other interested parties. This study meets the requirements of the international standards for Life Cycle Assessment (LCA) according to ISO 14040 (ISO, 2006) / ISO 14044 (ISO, 2006).

1.3. Scope of the study

Product systems, function and functional unit

The product systems to be studied are single-use, small to medium-size beverage packaging alternatives for carbonated (c) and non-carbonated drinks (nc). Beverages are not included.

Primary beverage packages under study are assumed to be technically equivalent regarding the mechanical protection of the packaged beverage during transport, the storage and at the point-of-sale.

PET bottles, glass bottles, AlumiTek bottle (ATB) and beverage cartons are resealable, while aluminum cans are not. The consequences of resealability are not considered in this study because of uncertainties related to the beverage contents and consumption patterns. Representative products have been selected by the commissioner of this study as they are considered to be competing products in the US.

The function of the compared products is to contain beverages, enabling transportation, and protecting beverages against mechanical stress and material loss up to their consumption. It is understood that the minimum legal standards applicable to products coming in direct contact with food and beverage for human consumption are fulfilled in all products in this study.

The functional unit is defined as 1 gallon of fill volume of small to medium-size, single-use beverage packaging at point of sale. The reference flow for the product systems is Beverage container (packed), including both the primary and the secondary packaging.

Table 1: Packaging products and scenarios under study for the US region (C: carbonated, NC: non-carbonated)

US				
Baseline			**Additional scenarios / sensitivity analyses**	
Material	**Sizes**	**EoL / Treatment of secondary materials**	**EoL / Treatment of secondary materials**	**Others**
Beverage cartons	11.2oz (0.33L)	Cut-off	Substitution	Beverage carton weight reduction by 5-10% Recycled content 0-100%
	16.9oz (0.50L)			
PET bottle (C)	12.0oz	Cut-off	Substitution	PET bottle weight reduction by 5-10% Manufacturing energy for blow molding Recycled content 0-100%
	16.9oz			
PET bottle (NC)	16.9oz			
Glass bottle (single use)	12.0oz	Cut-off	Substitution	Glass bottle weight reduction by 5-10% Recycled content 0-100%
	16.0oz			
Aluminum can	12.0oz	Cut-off	Substitution	Renewable energy for manufacturing Aluminum can weight reduction by 5-10% Recycled content 0-100%
	16.0oz			
	16.0oz (AlumniTek)			

System boundaries

The system boundaries are summarized in Table 2, displaying a cradle-to.-grave system from production of raw materials up to end-of-life.

Table 2: System boundaries

Included	Excluded
✓ Manufacturing of raw materials ✓ Transport of raw materials to manufacturing, if available ✓ Transport to filling station ✓ Secondary packaging ✓ Distribution to retailer ✓ Reuse, if applicable ✓ End of Life (incineration, landfill and recycling)	× Packaging of raw materials/pre-products × Production of beverages × Tertiary Packaging × Packaging to filling station × Filling and refilling process × Cooling of filled beverage containers × Capital Goods

Representativeness

The time reference for primary data collected for the aluminum cans is 2018. The time reference for all other beverage containers is also 2016-2019, as the products were purchased, weighed and measured in 2019 July through September. The intended technology reference is the most current available industry average; even though Ball has provided primary data for can manufacturing, the regional data included averages across various sites. The competing packaging products also aim to represent current industry averages. The geographical reference is the US region.

Multi-output allocation

Liquid packaging board (LPB, used to make composite carton beverage containers like those by Tetra Pak or Elopak) has been mass allocated.

Beyond this, there are no significant multi-output processes within the foreground system. As a result, all impacts from the foreground system are fully allocated to the products under study.

Allocation of background data (energy and materials) taken from the GaBi 2019 databases is documented online at http://www.gabi-software.com/deutsch/my-gabi/gabi-documentation/gabi-database-2019-lci-documentation/.

End of life allocation

End-of-Life (EoL) allocation generally follows the requirements of ISO 14044. In the US, the cut-off approach is adopted for the baseline scenario. Any open scrap inputs into manufacturing remain unconnected. As part of the system boundaries, scrap on the input side will be processed in the appropriate recycling/manufacturing step to make it useable as a raw material input (recycled content). The system boundary at end of life is drawn after scrap collection to account for the collection rate, which generates an open scrap output for the product system. The processing and recycling of the scrap output is associated with the subsequent product system and is not considered in this study. The system boundary includes the waste incineration and landfilling processes following the polluter-pays-principle. No credits for power or heat production are assigned.

The decision to rely on this method was made together with the commissioner, based on the regional significance and acceptance of the methodology. In order to also produce comparable results to other regions of the broader study, a substitution[1] approach was also included as an additional scenario.

Cut-off criteria

No cut-off criteria for the foreground system are defined for this study within the primary data collection. The system boundary was defined based on relevance to the goal of the study. For the processes within the system boundary, all available energy and material flow data have been included in the model.

LCIA methodology

TRACI 2.1 has been selected as it is currently the only impact assessment methodology framework that incorporates US average conditions to establish characterization factors (Bare, 2012) (EPA, Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) – User's Manual, 2012).

The impact assessment categories and other metrics considered to be of relevance to the goals of the study are shown in Table 3 and Table 4.

Table 3: TRACI 2.1 impact category descriptions

Impact Category	Description	Unit	Reference
Global Warming Air, excl. biogenic carbon	A measure of greenhouse gas emissions, such as CO_2 and methane.	kg CO_2 equivalent	(IPCC, 2013)
Eutrophication	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P).	kg N equivalent	(Bare, 2012) (EPA, Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) – User's Manual, 2012)
Acidification	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value.	kg SO_2 equivalent	As for Eutrophication

---

[1] Substitution approach: A value of scrap burden was calculated for the input amount of scrap metal (i.e. recycled content enters the product system with corresponding burdens), while recovered material at the End of Life was assigned a credit.
In cases where materials are sent to waste incineration, they are linked to an inventory that accounts for waste composition and heating value as well as for regional efficiencies and heat-to-power output ratios. Credits are assigned for power and heat outputs using the regional grid mix and thermal energy from natural gas.

Impact Category	Description	Unit	Reference
Smog Air	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light.	kg O_3 equivalent	As for Eutrophication
Ozone Depletion Air	A measure of air emissions that contribute to the depletion of the stratospheric ozone layer.	kg CFC-11 equivalent	As for Eutrophication
Ecotoxicity	A measure of toxic emissions which are directly harmful to the health of humans and other species.	Comparative toxic units (CTUh, CTUe)	(Rosenbaum, et al., 2008)

Table 4: Other environmental indicators for the US region

Indicator	**Description**	**Unit**	**Reference**
Blue water consumption	A measure of the net intake and release of fresh water across the life of the product system.	Liters of water	(thinkstep, 2014)

Material Circularity Indicator

In addition to the impact categories and LCI metrics discussed above, this report also explores the circularity of the products assessed. Circularity is increasingly included in political agendas.

The Material Circularity Indicator (MCI) scores are calculated for each product using the methodology described in *Circularity Indicators - An Approach to Measuring Circularity* (Ellen MacArthur Foundation & Granta Design, 2015). MCI scores are assessed on a scale from 0-1. One represents a theoretical perfectly circular product where all input and output flows are restorative and there are no losses associated with activities such as recycling.

Three main aspects of the product’s life cycle influence the MCI score:

- Proportion of input material flows that are restorative (i.e. from reused or recycled sources)
- Proportion of waste flows that are used restoratively (i.e. reused or recycled at end of life), including the efficiency of material recycling processes (material losses during recycling).
- Product utility compared to that of an average product in the market. This can relate to use intensity, serviceable lifetime, etc. For packaging applications, the number of refill cycles can be considered a suitable measure of product utility, with single use items being the average situation.

The current MCI methodology has been designed with a focus on non-renewable resources and the report does not go into details regarding how to assess renewable resources (e.g. paper, cardboard, biopolymers) – the Ellen MacArthur Foundation is in the process of further developing the methodology to evaluate how to deal with such materials. In this study it is assumed that renewable resource inputs such as fibers used in beverage cartons and secondary packaging are sourced sustainably. This is because some of the biggest producers of the paper and carton products assessed in this study have declared certified sustainable sourcing by the Forest Stewardship Council (FSC). As such, the position was adopted that these inputs are completely restorative and therefore resource scarcity is not considered as a concern.

Software and Databases

The LCA model was created using the GaBi 9 Software system and Service Pack 39 for life cycle engineering, developed by thinkstep (now sphera). The GaBi 2019 LCI database provides the life cycle inventory data for several of the raw and process materials obtained from the background system.

1.4. Life Cycle Inventory Analysis

Aluminum cans

Primary data were collected using customized data collection templates from Ball Corporation. Primary data covered can body and can end as well as AlumiTek bottle manufacturing for 3 sizes/types. Primary data also extended to the secondary packaging for selected final products that use Ball beverage cans and bottles.

PET bottles, glass bottles and beverage cartons

For all other beverage containers secondary data was collected based on sample products selected by Ball for most relevant market shares in the US. The final set of specific products is summarized in Table 5. The specified products were purchased, materials identified, measured and weighed to the precision available in-house. For most products, the precision of measurements was at least one decimal place (0.1g), giving a relative error of at most 10% by weight in case of caps (1-2g), but well under 1% relative to the entire primary packaging (bottle plus cap). For carton products produced by Tetra Pak, information on product weight and composition was taken from online resources (Tetra Pak 2019).

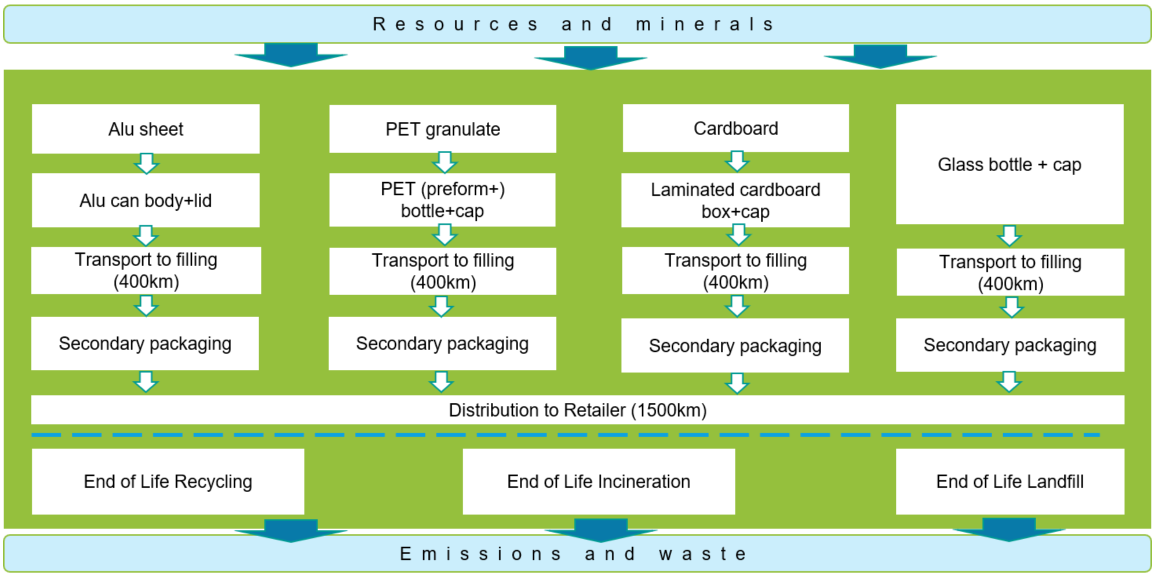


Figure 1: **Overview of system boundaries of the product systems investigated (without displaying details of materials)**

Table 5: Overview product specifications

Material	Primary									Secondary			
	Container Volume	Container Weight (g)	DQI*	Cap material	Cap Weight (g)	DQI*	Label	DQI*	Label Weight (g)	DQI*	Nesting	Packaging material	Weight (g)
Carton	11.1oz	13.00	L	HDPE	4.00	L	direct print	-	n/a	-	12	corrugated board	231
	16.9oz	18.60	M	HDPE	2.70	M		-	n/a	-	24	corrugated board	386
							direct print				1x24	corrugated board	1055
PET (C)	12oz	19.10	M	PP	2.04	M	LDPE	M	0.22	M	8	LDPE	5
											3x8	corrugated board	94
	16.9oz	26.00	M	PP	3.02	M	LDPE	M	0.86	M	6	LDPE	13
											4x6	corrugated board	149
PET (NC)	16.9oz	8.81	M	PP	1.06	M	LDPE	M	0.21	M	12	LDPE	14
Glass	12oz	288.00	M	tinplated steel	2.10	M	direct print	-	n/a	-	12	corrugated board	439
											1x12	corrugated board	532
	16oz	223.00	M	tinplated steel	4.10	M	paper	M	1.39	M	6	corrugated board	69
											4x6	corrugated board	149
Alu can	12oz	10.25	M	aluminum	2.43	M	direct print	M	n/a	M	8	corrugated board	66
	16oz	12.18	M	aluminum	2.43	M	direct print	M	n/a	M	4	corrugated board	50
	16oz (ATB)	21.97	M	aluminum	2.56	M	direct print	M	n/a	M	9	corrugated board	119

*DQI Data Quality Index: M – Measured, E – Estimated, L – Literature, ATB – Alumi-Tek Bottle, n/a – not applicable

Table 6: Recycled content of considered packaging alternatives

Beverage container	Recycled content	Source
Aluminum cans	73%[2]	(The Aluminum Association, 2019)
PET bottles	6%	(National Association of PET Container Resources (NAPCOR) and The Association of Plastic Recyclers (APR) , 2018)
Glass bottles	35%	Glass Packaging Institute (GPI, 2014)
Beverage carton	0% all virgin materials	Alliance for Beverage Carton and the Environment (ACE) (Ifeu, 2011)

Datasets used in the study

For modelling the aluminum cans, the most relevant datasets included:

- Ingot mix from the International Aluminum Association (IAI) dataset for the region North-America (RNA: Aluminium ingot mix IAI 2015) was used (World Aluminium, 2017);
- Aluminum sheet making (RNA: Combined hot and cold rolling) and remelting (RNA: Aluminum scrap remelting and casting) are GaBi datasets based on The Aluminum Association's data yet to be published in GaBi Databases 2010.

For the PET bottles the most relevant datasets included:

- PET granulate via PTA pathway (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/043fc939-8eff-409b-ac6b-7609312ab447.xml);
- To reflect the manufacturing steps, bottle blow molding originally developed for HDPE bottles (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/3979582f-0678-4dfe-8304-1860a797c0b8.xml) and an injection molding dataset for the closures was applied (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/aaf7c3a1-6ecd-459e-a493-3f376507e29b.xml). The resin for the closures was PP granulate (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/5bb0726a-a44f-4f80-a964-0aeeb947ad41.xml).

For the glass bottles the most relevant datasets included:

- Production of container glass (100% batch) (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/5f88e494-354b-4e7b-b40a-f734f7304642.xml) and Production of container glass (100% cullet) (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/497a4b72-84bf-4ba0-84ef-cf5ed9fd2a5b.xml) have both been regionalized to US boundary conditions.
- The closures were modelled as tinplated steel (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/4b6095ea-22c3-4509-9a8c-b81297551db4.xml).

For the beverage cartons the most relevant datasets included:

- The liquid Packaging Board dataset has been proxied with the FEFCO Kraftliner dataset (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/6ac37d3c-caeb-4216-9f1d-c78c1b8c772b.xml) regionalized to US boundary conditions.
- The LDPE film has been modelled with virgin granulate (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/1cab96fb-492d-436a-8f14-fd86df4f7843.xml) and plastic film making.

---

[2] According to the government-approved terminology of recycled content, which excludes run-around scrap. Total scrap input including run-around scrap amounts to 78%.

- The aluminum foil has been modelled using the European Aluminum association’s film dataset (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/86c4d1c5-19f9-4d43-9bff-0b88b714b93f.xml) combined with ingot mix from the International Aluminum Association (IAI) dataset for Region North America (see details under aluminum cans).

The complete list of used datasets can be found in the full report.

Table 7: Datasets used to model energy provision for products manufactured in the US.

Material	GaBi dataset	Source	Documentation	Reference year
Electricity	US: Electricity grid mix ts	ts	http://gabi-documentation-2019.gabi-software.com/xml-data/processes/6b6fc994-8476-44a3-81cc-9829f2dfe992.xml	2016
Thermal energy from natural gas	US: Thermal energy from natural gas ts	ts	http://gabi-documentation-2019.gabi-software.com/xml-data/processes/885a8641-0eae-4f2f-b191-cec7335325bc.xml	2016

Table 8: Most relevant datasets used to model material and product transport in the US.

Transport mode	GaBi dataset	Source	Documentation	Reference year
Truck-trailer	GLO: Truck-trailer, Euro 0 - 6 mix, 34 - 40t gross weight / 27t payload capacity	ts	http://gabi-documentation-2019.gabi-software.com/xml-data/processes/4e47891c-25ca-4263-8ebd-e1b462c0f4b8.xml	2016
Diesel	US: Diesel mix at refinery ts		http://gabi-documentation-2020.gabi-software.com/xml-data/processes/452a3926-2850-47db-809d-753095ed7dac.xml	2016

End of Life

For each product three possible end of life waste streams are available: recycling, incineration and landfill. The statistics for each of these end of life streams is sourced from the EPA Report 2015 (EPA, 2015) (annex 3) for all materials except for aluminum. Table 9 summarizes these statistics. Collection rates refer to values provided as collected for recycling. Losses due to sorting are not considered, yields refer to the efficiency of the recycling plant to convert a given post-consumer material into secondary materials and reflect data in the corresponding recycling dataset of the GaBi databases. These losses are most likely to affect materials, whose sorting efficiencies are lower, such as plastics and beverage cartons, thereby disadvantaging aluminum and glass, which are easier to sort. Transport distances to End of Life processing facilities are neglected, as these are expected to be within 100 km radius of the disposal site by the end consumer.

Table 9: End of Life treatment of considered packaging alternatives in the US region

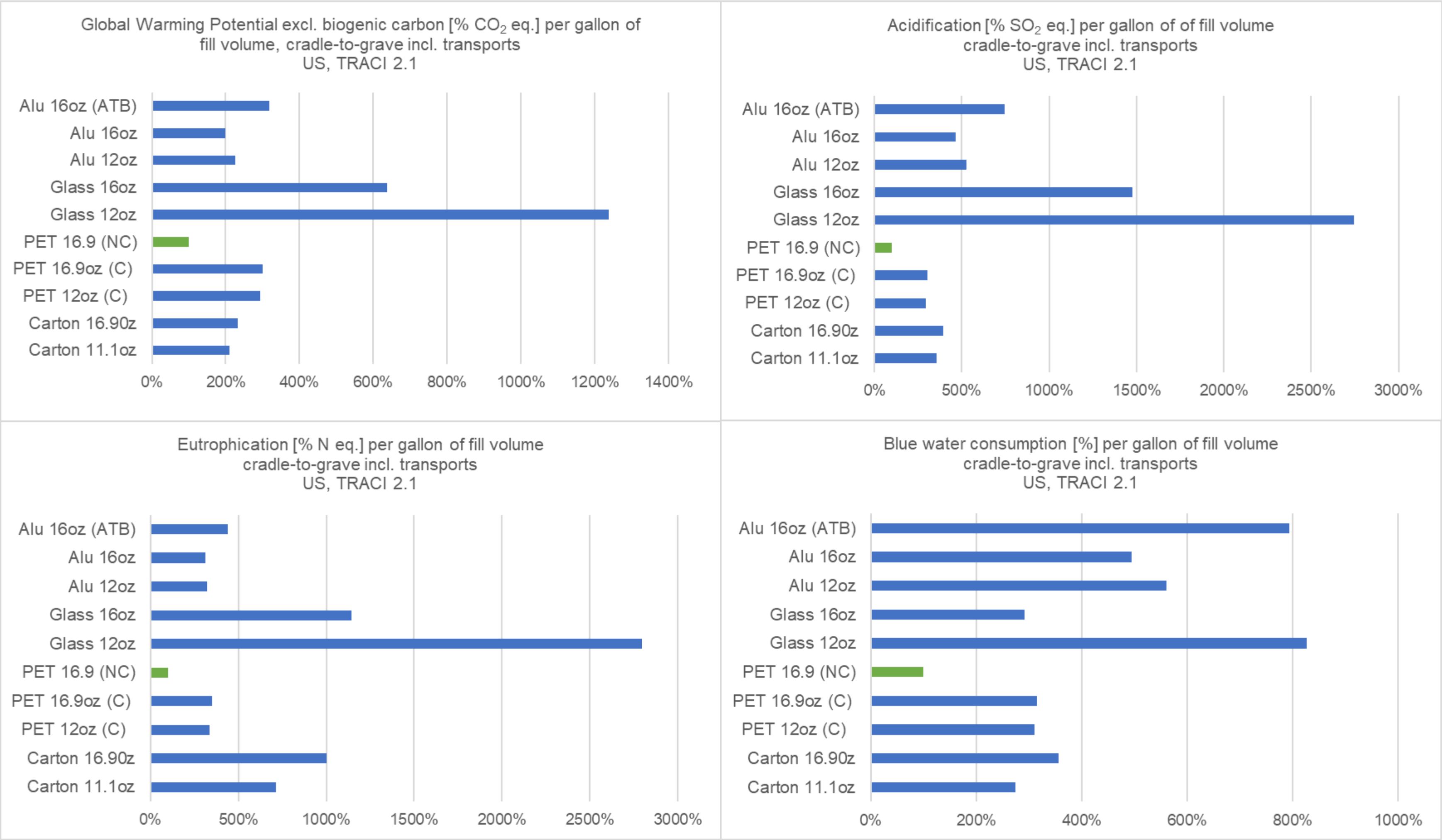
	EoL stream	Collection %	Yield %	Source
Aluminum can	Recycling	50.4	98	AA 2016
	Incineration	0	-	
	Landfill	49.6	-	
PET bottle	Recycling	29.9	86	EPA 2015
	Incineration	13.8	-	
	Landfill	56.4	-	
Glass bottle	Recycling	41.9	97	
	Incineration	11.5	-	
	Landfill	46.6	-	
Beverage cartons	Recycling	26.4	92*	
	Incineration	14.4	-	
	Landfill	59.1	-	

*Recycling yield of beverage cartons only refers to the paper fraction, the aluminum and polyethylene fractions have been assumed to have 0% material recycling yield.

1.5. Life Cycle Impact Assessment

The LCIA results include contribution analyses, which split the results according to the following life cycle stages: manufacturing, secondary packaging, transport to filling, distribution and end of life. This enables the reader to understand the influence of each life cycle stage on the overall environmental performance of the product. LCIA results are relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

This summary report contains the details of the global warming potential (GWP) impact category only for brevity. While this is a robust and globally highly relevant impact category, a comparative life cycle assessment should never rely on a single impact category, which is why the full report duly discusses acidification potential, eutrophication potential, and blue water consumption along with GWP. Figure 2 provides an overview of the four selected impact categories: The 100% value is the smallest result in each impact category, and other products are provided in relative terms as percentages.



Global Warming Potential excl. biogenic carbon [% CO_2 eq.] per gallon of fill volume, cradle-to-grave incl. transports US, TRACI 2.1

Acidification [% SO_2 eq.] per gallon of of fill volume cradle-to-grave incl. transports US, TRACI 2.1

Eutrophication [% N eq.] per gallon of fill volume cradle-to-grave incl. transports US, TRACI 2.1

Blue water consumption [%] per gallon of fill volume cradle-to-grave incl. transports US, TRACI 2.1

Figure 2: Overview of selected impact categories explored in the full report. Results refer to the full life cycle (cradle to grave, scaled to gallon of fill volume), in relative terms, showing the product with the lowest impact as 100% (in green).

Global Warming Potential (GWP) – beverage packaging comparison

GWP is driven by greenhouse gases like CO_2 and CH_4 in the troposphere which trap infrared radiation and redirect it back towards the Earth's surface. This radically alters the conditions at the Earth's surface and may cause warming or cooling effects which have the potential to alter weather events, affect ocean current circulation and cause other long-term GWP effects.

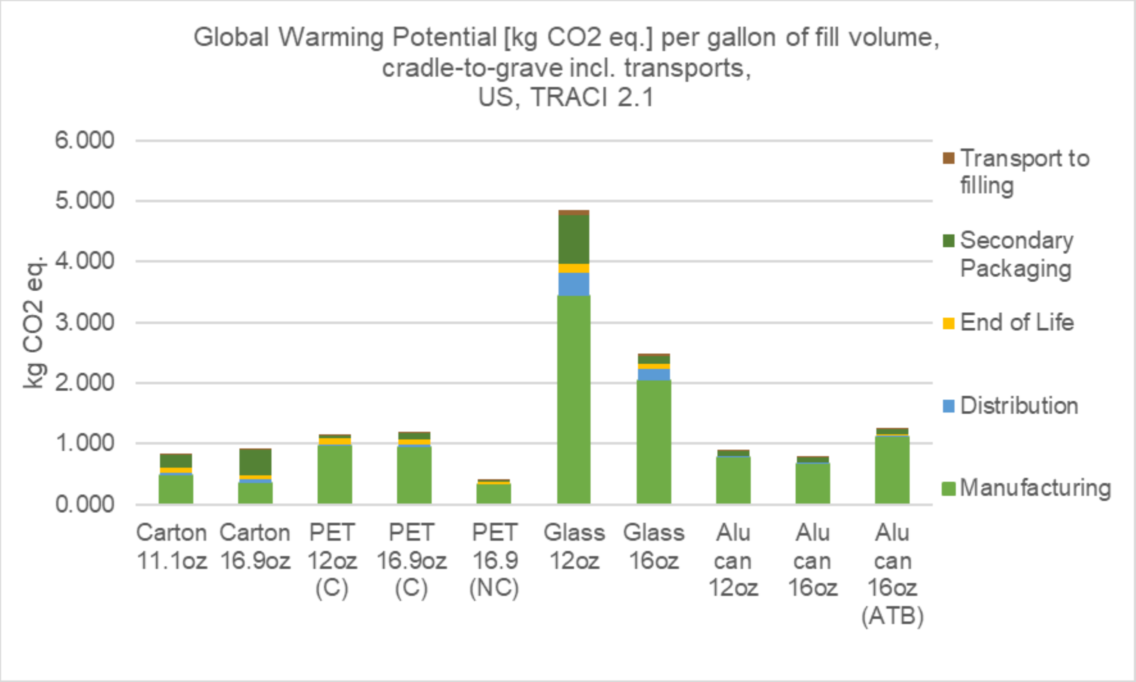


Figure 3: **The contribution of different life cycle stages/production processes to the overall GWP results, scaled to 1 gallon liter of fill volume, cradle-to-grave including transports, using the TRACI 2.1 method.**

The 16.9oz PET bottle for non-carbonated water has the lowest impact overall due to its extremely thin-wall design. The second place among non-carbonated drinks packaging is a close match between aluminum cans and beverage cartons, with very similar overall burdens. Glass bottles, by a large margin, come in last. Among options for carbonated drinks, aluminum performs strongest, followed by PET bottles and finally glass. The low mass and high recycled content of aluminum cans enable consistently low impacts of this packaging format. The lightweight nature of the PET bottles makes them an efficient packaging format, where the majority of climate change impacts are coming from the fossil-based raw materials.

Cartons show a low GWP because they are predominantly made from virgin paperboard. This paperboard is sourced from biomass and also uses large amounts of biomass as fuel for the pulp and papermaking process (from bark, forestry off cuts, wood chips, black liquor, etc.). Biogenic carbon dioxide is sequestered during tree growth, which is then re-emitted when incinerated (for energy) resulting in a zero overall net emission of greenhouse gases (GHG). The lack of GHG emissions associated with these biomass fuels significantly reduces the overall GWP of beverage cartons.

Glass bottles are the packaging format with the highest GWP. This reflects the energy-intensive manufacturing process and the far larger mass of glass bottles compared to other packaging options. Per gallon of beverage, the 12oz bottle has markedly higher burdens than the 16oz bottle. This is due to the increased packaging efficiency per gallon as pack sizes increase (larger packs use less mass per unit of volume than smaller packs). The burdens related to secondary packaging for the 12oz glass bottle are higher for the same reason.

Cartons also show a relatively large contribution from secondary packaging. For the 16.9oz pack this has higher burdens than the carton itself and can be explained by the high proportion of recycled paper in the corrugate boxes. Paper recyclers often do not have access to biomass fuel that is readily available for use by virgin producers, and so have to rely more on fossil fuels. As such, GWP burdens for recycled content can be higher than for virgin material.

Apart from the 16.9oz carton, the manufacturing stage is the dominant contributor to the environmental burdens for GWP for all packaging options assessed in this study.

Global Warming Potential – aluminum can hotspot analysis

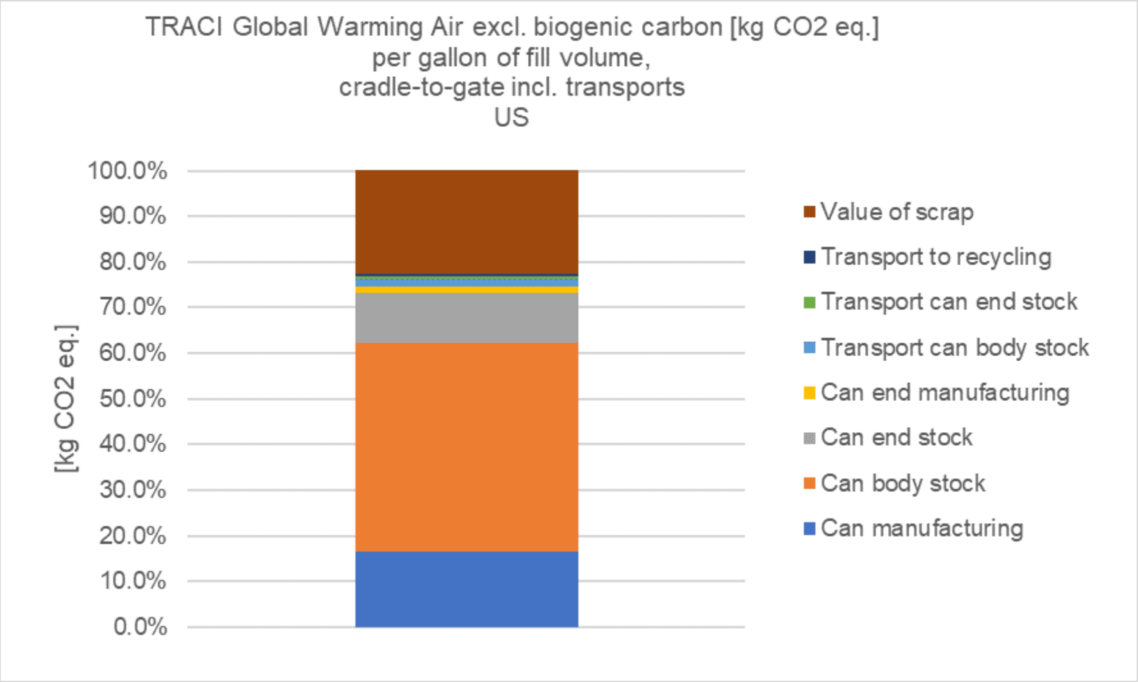


Figure 4: Detailed global warming potential contributions in the manufacturing phase of the 12oz aluminum can, shown per liter of per fill volume, using the TRACI 2.1 method (substitution method).

Figure 4 shows the contribution analysis within aluminum can manufacturing. This analysis was run using the substitution methodology to demonstrate the environmental impact of recycled content (“Value of scrap”). The contribution analysis shows the “can body stock” or smelting process accounts for just under 50% of the total GWP derived from cradle-to-gate, due to this being a very energy-intensive process. The GWP related to the remaining manufacturing processes are predominantly derived from the mining and processing of raw bauxite material used to manufacture aluminum and turn it into can end and body stock. The can manufacturing process accounts for ~19% of the overall burdens of production. Burdens from transport processes are <1%. The high end of life recycling rate and the credits received for recycling at end of life will, to a large extent, be offset by the burdens of the input scrap when the full cradle-to-grave scope is assessed using the substitution approach.

1.6. Uncertainty and variability: sensitivity and scenario analyses

In order to account for potential variability within the foreseeable future as well as for uncertainties in a few parameter values and methodological choices, scenarios and sensitivity analyses are discussed. Here we explore the sensitivity of the results to parameters whose variation was expected to make significant differences to the outcomes. Parameters were shortlisted based on uncertainty due to data quality and the authors' expert judgment on relevance to the results.

The following section summarizes two aspects of variation explored in the results of this study. The first aspect describes the uncertainty in GWP for each packaging format assessed, with respect to data quality and methodology. The second aspect describes the potential variability of GWP of each packaging type based on sensitivity analyses performed to assess *potential for change in the future*. Together, the results are intended to show the maximum potential improvements and worst-case outcomes identified for each packaging type. Ultimately, this chapter is designed to allow the reader to understand the reliability of the results and identify the maximum potential improvement in performance for each packaging type by adopting the changes defined in the sensitivity analyses.

Thus, the uncertainty analysis presented in Figure 5 considered the following scenario and sensitivity analyses:

- Methodology of secondary materials and End of Life treatment of waste (Substitution vs cut-off)
- PET bottle manufacturing (2x and 0.5x baseline energy consumption for blow molding)

In addition to the above uncertainties, further variability was included in Figure 6 to account for potential future change:

- Product lightweighting (-10% product weight)
- Recycled content 0-100%
- 100% renewable energy for aluminum can manufacturing

Table 10: Summary of scenario and sensitivity analyses in the US region for TRACI 2.1 Global Warming Air [kg CO2 eq.] impact of products scaled to 1 gallon of fill volume, cradle-to-grave incl. transports, and calculation of variability by means of minimum and maximum values. Grey cells denote the lack of a corresponding scenario / sensitivity analysis.

			Uncertainty			Future change potential			
		Baseline	Scenario	Sensitivity analyses		Scenario	Sensitivity analyses		
Material	Sizes	Cut-Off	Substitution	PET mfg energy consumption (15% more)	PET mfg energy consumption (15% less)	Renewable energy for can mfg	Lightweighting (10% less)	Recycled content (0%)	Recycled content (100%)
Beverage cartons	11.2oz	0.82	0.78				0.77	0.82	0.85
	16.9oz	0.91	0.88				0.86	0.91	0.93
PET bottle (C)	12oz	1.15	0.99	1.38	0.92		1.04	1.15	0.58
	16.9oz	1.17	1.02	1.41	0.94		1.07	1.17	0.63
PET bottle (NC)	16.9oz	0.39	0.34	0.47	0.31		0.36	0.39	0.21
Glass (single use)	12oz	4.85	4.72				4.45	5.69	3.28
	16oz	2.49	2.40				2.26	2.98	1.58
Aluminum can	12oz	0.88	1.05			0.79	0.82	2.12	0.48
	16oz	0.78	0.93			0.67	0.73	1.85	0.43
	16oz (ATB)	1.25	1.46			1.04	1.15	2.91	0.63

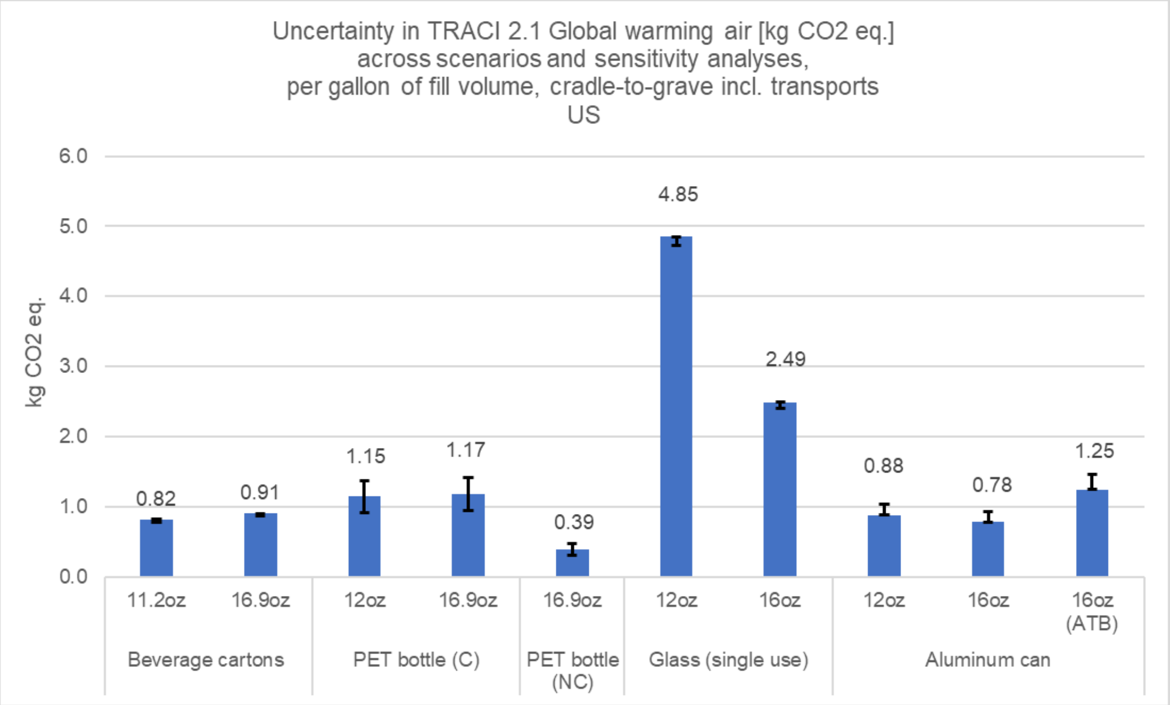


Figure 5: Uncertainty analysis of the TRACI 2.1 Global Warming Air [kg CO2 eq.] of products scaled to 1 gallon of fill volume, across various scenarios and sensitivity analysis. Values taken from Table 10: baseline – cut-off, min – minimum of values from scenario and sensitivity analyses under the column “Uncertainty”, max– maximum of values from scenario and sensitivity analyses under the column “Uncertainty”.

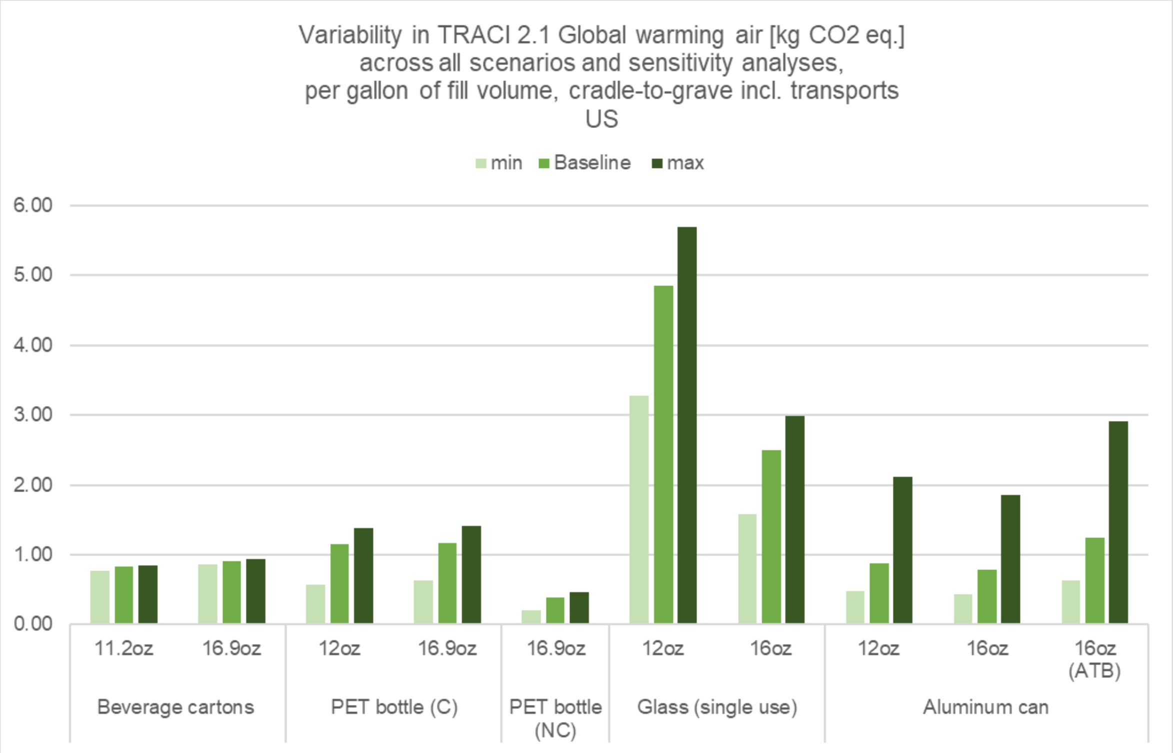


Figure 6: Variability analysis of the TRACI 2.1 Global Warming Air [kg CO2 eq.] of products scaled to 1 gallon of fill volume, cradle-to-grave incl. transports, across all scenarios and sensitivity analysis. Values taken from Table 10: baseline – cut-off, min – minimum of values from all scenario and sensitivity analyses, max– maximum of values from all scenario and sensitivity analyses.

There is little recorded uncertainty for the beverage cartons (Figure 5) and little improvement potential found in the variability analysis (Figure 6). This is because the cartons are not significantly affected by methodological differences in the underlying recycling methodology for the study. When increasing the amount of recycled content beverage cartons’ GWP even increases slightly. Paperboard manufactured from virgin fiber produces side products can be used as a biofuel and provide energy for the pulp and papermaking processes (from bark, forestry off cuts, wood chips, black liquor, etc.). By contrast, recycled paperboard manufacturing does not produce these energy-rich by-products and is therefore often reliant on external, fossil energy resources (grid), which have a higher GWP than the carbon-neutral internal bio-based fuels.

PET bottles show a degree of uncertainty around the baseline impact recorded (Figure 5) which is related to uncertainties in the amount of energy consumed during the PET blow-molding manufacturing process and differences in the chosen recycling methodology. PET bottles show a significant potential for improvement overall (Figure 6), as they show a medium response to improvements in the recycled content.

Single use glass bottles show higher uncertainty related to the recycling methodology used, but also shows great potential for improvement dependent upon the recycled content and product weight.

Aluminum cans demonstrate a higher level of variability, which is derived from differences in the climate change impact found for the baseline recycling methodology and alternative (substitution) recycling methodology. The cans also have a significant potential for improvement based on the recycled content and switching the electricity grid mix supply used for manufacturing from fossil-based to renewable.

1.7. Material Circularity Indicator

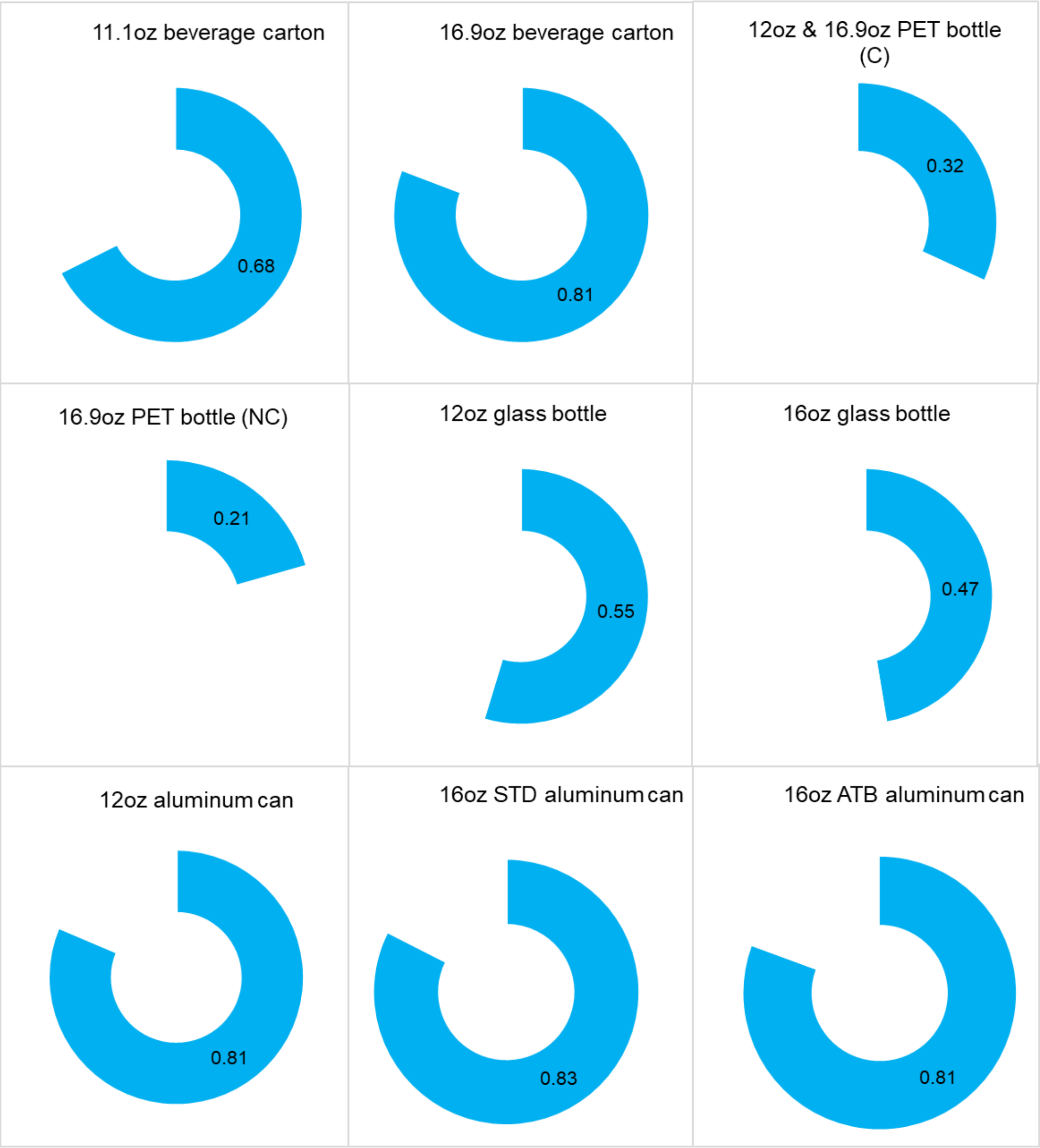


Figure 7: Material Circularity Indicator results for the different packaging options

A score of 1 indicates a completely circular product, and a score of 0.1 indicates a completely linear product. This means that conversely to all previous environmental impact charts, a higher MCI value indicates a better material circularity performance.

As shown in Figure 7, Aluminum cans have the highest MCI scores of ~0.8, which reflects the high rate of recycled content (73%) and – compared to other substrates – high recycling rate at end of life (50%). Variability in the MCI scores for different can sizes derive from differences in the secondary packaging used.

Beverage cartons have an intermediate MCI score of around 0.7-0.8. This is because cartons contain 69-74% paperboard, which is assumed to be sustainably sourced and therefore (based on the MCI methodology) restorative (circular) in nature. Tetra Pak beverage cartons in the US are manufactured using paperboard, of which 100% is derived from Forestry Stewardship Council (FSC) certified or controlled sources (Tetra Pak, 2018). Additionally, relatively large quantities of secondary packaging made of cardboard are applied for these products, which are also assumed to be restorative (circular) and have a high recycling rate at end of life, thus further increasing the total

MCI. Provided that the carton in the primary packaging is not sourced sustainably, the MCI would be considerably lower. As explained before, the MCI is calculated based on material fractions independent of total amounts, therefore some results go contrary to principles of waste and material efficiency as well as results of traditional LCIA.

Glass bottles have an intermediate MCI score of around 0.5 because both options have an assumed recycled content of 35% and a recycling rate at end of life of 42%.

PET bottles have the lowest MCI scores among the packaging formats assessed in this study, with values from 0.2 to just over 0.3. This is because the PET bottles are made of 94% virgin material and have a relatively low collection rate of 30% at end of life.

1.8. Interpretation

Assumptions and Limitations

Data quality differences between the subjects of the comparison, specifically, the primary data-based aluminum cans and the secondary data-based alternative packaging products pose the most critical limitation to the study.

Consequently, conservative assumptions have generally been taken with respect to the aluminum can to avoid any misrepresentation of results and unfair treatment of the competitive products.

Product ranking/performance

- The single overall best performer in the selected impact categories in this study is the 16.9oz PET bottle for non-carbonated water, due to a very thin-walled bottle design, resulting in favorable packaging-to-product ratio.
- Second and third place for non-carbonated beverage packaging alternates between aluminum cans and beverage cartons. While beverage cartons have the stronger overall performance for acidification and blue water consumption, aluminum performs better on eutrophication. Beverage cartons and standard aluminum cans perform equally well on GWP.
- Among the options for carbonated beverages, aluminum cans are the strongest performers on GWP and eutrophication, while PET bottles show lower impacts in blue water consumption and acidification.
- PET bottles fare well due to relatively low virgin material impacts and manufacturing-related impacts. At the same time, this means that unlike for aluminum cans and glass bottles, the use of recycled material does not result in significant improvements for most of the environmental impact categories.
- Cartons generally show good environmental performance because the main raw material, paperboard (typically around 70% (w/w) of the carton) tends to have low manufacturing impacts. Paperboard is often produced in an integrated pulp and paper mill will have most of the required energy derived from biomass such as wood offcuts from forestry, bark and wood chips and from black liquor produced from the wood during pulp production. Many integrated paperboard mills export excess electricity to the grid, further reducing the production burdens.
- The strong performance of aluminum cans can largely be attributed to the lightweight nature of the product compared to other packaging types, the high recycled content (73%) and the decent recycling rate (when compared to other substrates) of 50% at end of life.
- Although already high in recycled content, aluminum cans display the highest potential for improvement via further increases in recycled content. Conversely, the impact of aluminum cans is also most sensitive to drops in recycled content. As indicated previously, the least

sensitive to this parameter, are beverage cartons, that show even a small increase in GWP when increasing recycled content.

- Glass bottles show the highest impacts among the assessed packaging formats. This is because they are much heavier than the other packaging types and glass production is also relatively resource and energy intensive. Reusable glass bottles were not assessed for this region because their market share in the US is close to 0%.
- When assessing the results using the substitution recycling methodology instead of the cut-off approach fairly minor differences in the results were observed. For most products, the amount of recycled content used as input to packaging manufacture correlates with collection for recycling at end of life. Under these conditions, both substitution and cut-off approaches provide similar results. The substitution approach gives greater burdens than the cut-off approach for products that possess more recycled content than is recycled at end of life, and vice versa. Aluminum cans showed the greatest discrepancy in results of 18% between the two methodologies because the proportion of recycled content is higher than the actual recycling rate. Contrary to aluminum cans, PET bottles benefit from the substitution method since they are predominantly based on virgin granulate (6% recycled content) and have a medium collection rate (30%), which results in material credits.
- Shifting the electricity grid mix for can manufacturing from fossil-based to renewable energy (as already signed by Ball Corporation) reduces the climate change impacts of the aluminum cans and bottles between 11-16% (depending on can/bottle size) over the entire life cycle. Similar actions have the power to improve the impact of other packaging designs as well, although to a lesser degree. Beverage cartons are already assumed to rely largely on renewable energy from the pulping by-products, the impact of PET bottles is determined largely by the granulate.
- Lightweighting has a small but relevant potential to improving environmental performance, mostly for PET bottles, glass bottles and aluminum cans.
- Because of the uncertainty in data quality of PET blow molding, an additional manufacturing energy sensitivity analysis was performed for the PET bottle and showed a moderate sensitivity, with 7-15% impact change resulting from halving and doubling energy consumption, respectively.
- Although manufacturing of the primary packaging dominates most impact categories, secondary packaging does become dominant in the impact categories eutrophication and freshwater consumption, where carton in secondary packaging contributes more than half of the total life cycle of some of the beverage cartons and glass bottles, due to water-intensive processes at the paper and recycling mills.

Conclusions and recommendations

- Packaging efficiency has a significant impact on the environmental burdens of the packaging. A packaging container with a larger volume requires relatively less material to provide a given quantity of product. This is an important factor to consider when making comparisons across different packaging formats and sizes. It is important to note here, that the study focused on small-to-medium sized products, not all beverage packaging types and formats.
- Among non-carbonated beverages, thin-walled PET bottles for water stand out in performance in all four selected impact categories due to them being lightweight, with little secondary packaging and relatively low manufacturing energy demand. A combination of low recycling rates at end of life and lack of recycled content, leave a marked potential for future improvement for this packaging option.
- Aluminum cans show low impacts partly because they are lightweight, so less material is needed to manufacture them, but mainly because of the high average levels of recycled

content used during manufacturing and the high recycling rates at end of life. Design for a circular economy coupled to a greening of energy supply for manufacturing enables this packaging format to reach its potential for future improvement.

- Hotspot analysis of the aluminum can reveals that the most significant contribution to environmental impacts are derived from the can body stock (and value of scrap, denoting the theoretical impact of aluminum scrap) during the manufacturing phase. Given the high yield of aluminum recycling, the easiest way to reduce this impact is by closing the loop, i.e. by increasing collection rate and recycled content. While can manufacturing energy is not negligible, most energy consumption occurs further upstream in aluminum production, and to a lesser degree in sheet rolling, and thus energy efficiency measures and provision of renewable energy in those parts of the supply chain have more improvement potential. Certainly, further lightweighting can further reduce the overall impact of cans, too.
- Cartons have less potential to improve through increasing recycling rates as the paper recycling process is much less beneficial compared to the virgin process than is the case for aluminum. For some impact categories, recycling paper may be more impactful than virgin production, as recyclers do not have access to the large quantities of biomass fuel that is available to integrated pulp and paper mills. Certainly, renewable energy can be purchased also by recyclers and integrated virgin and recycled paper mills also exist sharing the benefits of renewable energy carrier by-products.
- With respect to circularity, it can be said that for a given material option (e.g. aluminum cans) the MCI often correlates quite well with findings on GWP, i.e. the higher the MCI, the lower the GWP. Aluminum cans tend to outperform other packaging materials, as a result of the highly developed infrastructure for collection, highly efficient material recycling technology, very high levels of recycled content, and extremely low yield losses during recycling, closing the loop rather well. However, the correlation between MCI and GWP is not a causal relationship because MCI scores do not measure material efficiency during production processes. Therefore, when comparing the MCI performance of different packaging materials, it should be noted that this correlation does not necessarily mean the packaging material with the highest MCI score has the best environmental performance overall.
- The study findings indicate the paramount importance of enhancing circular systems for high-value / high-impact materials such as aluminum, glass or (to a lesser degree) PET by
    - Increasing recycled content as far as technologically feasible,
    - Increasing collection rates at the end of life,
    - Maximizing refill cycles of bottles designed for reuse,
    - Supporting the logistics of closing the loop, i.e. providing the scrap input in the quality and quantity that is required by the input side.

1.9. References

Tetra Pak. (2018). *FSC Certification, Labelling and Verification.* Retrieved from Tetra Pak: https://www.tetrapak.com/sustainability/cases-and-articles/fsc-certification

Azevedo, L. (2014). *Development and application of stressor – response relationships of nutrients.* Radboud University Nijmegen.

Azevedo, L., Henderson, A., van Zelm, R., Jolliet, O., & M.A.J., H. (2013a). Assessing the Importance of Spatial Variability versus Model Choices in Life Cycle Impact Assessment: The Case of Freshwater Eutrophication in Europe. *Environmental Science & Technology, 47 (23)*, 13565-13570.

Azevedo, L., van Zelm, R., Elshout, P., Hendriks, A., Leuven, R., Struijs, J., . . . Huijbregts, M. (2013b). Species richness–phosphorus relationships for lakes and streams worldwide. *Global Ecology and Biogeography, 22 (12):*, 1304-1314.

Bare, J. (2012). *Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) - Software Name and Version Number: TRACI version 2.1 - User's Manual.* Washington, D.C.: U.S. EPA.

Bos, U., Horn, R., Beck, T., Lindner, J., & Fischer, M. (2016). *LANCA® -Characterisation Factors for Life Cycle Impact Assessment, Version 2.0.* Stuttgart: Fraunhofer Verlag.

BSI. (2012). *PAS 2050-1:2012: Assessment of life cycle greenhouse gas emissions from horticultural products.* London: British Standards Institute.

BSI. (2012). *PAS 2050-1:2012: Assessment of life cycle greenhouse gas emissions from horticultural products.* London: British Standards Institute.

Cempre. (2018). *Articles and Publications: Aseptic Carton.* Retrieved 04/ 2020, from Compromisso Empresarial Para Reciclagem: http://cempre.org.br/artigo-publicacao/ficha-tecnica/id/9/embalagens-longa-vida

Cempre. (2018). *Articles and Publications: Aseptic Cartons.* Retrieved 04/ 2020, from Compromisso Empresarial Para Reciclagem: http://cempre.org.br/artigo-publicacao/ficha-tecnica/id/9/embalagens-longa-vida

Cempre. (2018). *Articles and Publications: End of Life Statistics Corrugated Paper.* Retrieved 04/ 2020, from Compromisso Empresarial Para Reciclagem: http://cempre.org.br/artigo-publicacao/ficha-tecnica/id/3/papel-ondulado

Cempre. (2018). *Articles and Publications: Glass.* Retrieved 04/ 2020, from Compromisso Empresarial Para Reciclagem: http://cempre.org.br/artigo-publicacao/ficha-tecnica/id/6/vidro

Cempre. (2018). *Articles and Publications: Paper Labels.* Retrieved 04/ 2020, from Compromisso Empresarial Para Reciclagem: http://cempre.org.br/artigo-publicacao/ficha-tecnica/id/2/papel-de-escritorio

Cempre. (2018). *Articles and Publications: PET.* Retrieved 04/ 2020, from Compromisso Empresarial Para Reciclagem: (CEMPRE) http://cempre.org.br/artigo-publicacao/ficha-tecnica/id/8/pet

Cempre. (2018). *Articles and Publications: PET.* Retrieved 04/ 2020, from Compromisso Empresarial Para Reciclagem: http://cempre.org.br/artigo-publicacao/ficha-tecnica/id/8/pet

Cempre. (2018). *Articles and Publications: Plastics.* Retrieved 04/ 2020, from Compromisso Empresarial Para Reciclagem: http://cempre.org.br/artigo-publicacao/ficha-tecnica/id/4/plasticos

Cempre. (n.d.). *Articles and Publications: Steel Caps.* Retrieved 04/ 2020, from Compromisso Empresarial Para Reciclagem: http://cempre.org.br/artigo-publicacao/ficha-tecnica/id/1/latas-de-aco

De Baan, L., Alkemade, R., & Köllner, T. (2013). Land use impacts on biodiversity in LCA: A global approach. *national Journal of Life Cycle Assessment, 18 (6)*, 1216-1230.

De Schryver, A., Van Zelm, R., Humbert, S., Pfister, S., McKone, T., & Huijbregts, M. (2011). Value choices in life cycle impact assessment of stressors causing human health damage. *Journal of Industrial Ecology, 15 (5)*, 796-815.

Dr.-Ing. Joachim Harder, O. C. (2018, 05). *recovery*. Retrieved from https://www.recovery-worldwide.com/en/artikel/glass-recycling-current-market-trends_3248774.html

Drielsmaa, J., Russell-Vacari, A., Drnek, T., Brady, T., Weihed, P., Mistry, M., & Perez Simbor, L. (2016). Mineral resources in life cycle impact assessment—defining the path forward. *International Journal of Life Cycle Assessment*, 85-105.

Elshout, P., Van Zelm, R., Karuppiah, R., Laurenzi, I., & Huijbregts, M. (2014). A spatially explicit data-driven approach to assess the effect of agricultural land occupation on species groups. *The International Journal of Life Cycle Assessment, 19 (4)*, 758-769.

EPA. (2012). *Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) – User's Manual.* Washington, D.C.: U.S. EPA.

EPA. (2015). *Advancing Sustainable Materials Management: Facts and Figures Report.* Retrieved 04/ 2020, from United States Environmental Protection Agency: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management

EPA. (2018). *Advancing Sustainable Materials Management: 2015 Tables and Figures.* Retrieved 04/ 2020, from United States Environmental Protection Agency: https://www.epa.gov/sites/production/files/2018-07/documents/smm_2015_tables_and_figures_07252018_fnl_508_0.pdf

European Aluminium Association. (2013). *Environmental Profile Report for the European Aluminium Industry .* European Aluminium Association.

European Aluminum. (2018). *Environmental Profile Report. Life-Cycle inventory data for aluminium.* European Aluminum.

European Comission. (2018). *Default paramters CFF.* Retrieved 04/ 2020, from https://ec.europa.eu/environment/eussd/smgp/pdf/CFF_Default_Parameters_March2018.xlsx

European Comission. (2020). *Results and deliverables of the Environmental Footprint pilot phase*. Retrieved 04/ 2020, from https://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm

European Commission, J. R.-I. (2011). International Reference Life Cycle Data System (ILCD) Handbook- Recommendations for Life Cycle Impact Assessment in the European context. Luxemburg: European Commission.

Fantke, P., Evans, J., Hodas, N., Apte, J., Jantunen, M., Jolliet, O., & McKone, T. (2016). Health impacts of fine particulate matter. *Global Guidance for Life Cycle Impact Assessment Indicators: Volume 1. UNEP/SETAC Life Cycle Initiative*, pp. 76-99.

FEVE. (2018). *Raise The Glass.* The European Container Glass Federation.

Frischknecht, R., Braunschweig, A., Hofstetter, P., & Suter, P. (2000). Modelling human health effects of radioactive releases in Life Cycle Impact Assessment. *Environmental Impact Assessment Review, 20 (2)*, 159-189.

GPI. (2014, 09). *Achieving 50% Recycled Content for Glass Containers.* Retrieved from http://gpi.org/sites/default/files/GPI%20Recycled%20Content%20Report%2C%20September%202014.pdf

Graedel, T., & Reck, B. (2015). Six Years of Criticality Assessments - What Have We Learned So Far? *Journal of Industrial Ecology*. doi:10.1111/jiec.12305

Guinée, J. B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., . . . Huijbregts, M. (2002). *Handbook on life cycle assessment. Operational guide to the ISO standards.* Dordrecht: Kluwer.

Hayashi, K., Nakagawa, A., Itsubo, N., & Inaba, A. (2006). Expanded Damage Function of Stratospheric Ozone Depletion to Cover Major Endpoints Regarding Life Cycle Impact Assessment. *The International Journal of Life Cycle Assessment, 11 (3)*, 150-161.

Helmes, R., Huijbregts, M., Henderson, A., & Jolliet, O. (2012). Spatially explicit fate factors of phosphorous emissions to fresh water at the global scale. *International Journal of Life Cycle Assessment, 17 (5)*, 646-654.

ICF International . (2016). *Analysis of the Energy and Greenhouse Gas Emission Implications of Distributing and Refrigerating Beverages.* https://www.aluminum.org/sites/default/files/AluminumCanUse_Report_Clean%20Final_07-22-2016.pdf: Aluminum Association.

Ifeu. (2011). *LCI dataset for converting of beverage carton packaging material.* Heidelberg: Institute for Energy- and Environmental Research.

Ifeu. (2011). *LCI dataset for Liquid Packaging Board (LPB) production.* Heidelberg: Institute for Energy- and Environmental Research.

Ifeu. (2017). *Comparative Life Cycle Assessment of TetraPak® carton packages and alternative packaging systems for liquid food on the Nordic market.* Heidelberg: Institute for Energy- and Environmental Research.

IPCC. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories - Volume 4 - Agriculture, Forestry and Other Land Use.* Geneva, Switzerland: IPCC.

IPCC. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories - Volume 4 - Agriculture, Forestry, and Other Land Use.* Geneva, Switzerland: IPCC.

IPCC. (2013). *Climate Change 2013: The Physical Science Basis.* Geneva, Switzerland: IPCC.

IPCC. (2013). *Climate Change 2013: The Physical Science Basis.* Genf, Schweiz: IPCC.

ISO. (2006). *ISO 14040: Environmental management – Life cycle assessment – Principles and framework.* Geneva: International Organization for Standardization.

ISO. (2006). *ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines.* Geneva: International Organization for Standardization.

JRC. (2010). *ILCD Handbook: General guide for Life Cycle Assessment – Detailed guidance. EUR 24708 EN* (1st ed.). Luxembourg: Joint Research Centre.

Köllner, T., & and Scholz, R. (2007). Assessment of land use impacts on the natural environment. Part 1: An analytical framework for pure land occupation and land use change. *International Journal of Life Cycle Assessment 12*, 16-23.

Nassar, N., Barr, R., Browning, M., Diao, Z., Friedlander, E., Harper, E., . . . Graedel, T. (2012). Criticality of the Geological Copper Family. *Environmental Science & Technology*, 1071-1078.

National Association of PET Container Resources (NAPCOR) and The Association of Plastic Recyclers (APR) . (2018). *Report on Postconsumer PET Container Recycling Activity in 2017 .* National Association of PET Container Resources (NAPCOR).

Pfister, S., Koehler, A., & Hellweg, S. (2009). Assessing the Environmental Impacts of Freshwater Consumption in LCA. *Environ. Sci. Technol., 43(11)*, 4098–4104.

Pfister, S., Koehler, A., & Hellweg, S. (2009). Assessing the Environmental Impacts of Freshwater Consumption in LCA. *Environ. Sci. Technol., 43(11)*, 4098–4104.

Rosenbaum, R. K., Bachmann, T. M., Swirsky Gold, L., Huijbregts, M., Jolliet, O., Juraske, R., . . . Hauschild, M. Z. (2008). USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *Int J Life Cycle Assess, 13(7)*, 532–546.

Struijs, J., van Wijnen, H., van Dijk, A., & Huijbregts, M. (2009). *ReCiPe 2008.A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation factors, first edition.*

The Aluminum Association. (2019, September). *The Aluminum Can Advantage - Key Sustainability Performance Indicators .* Retrieved from The Aluminum Association: https://www.aluminum.org/sites/default/files/KPI%20Report%202019.pdf

thinkstep. (2014). *GaBi LCA Database Documentation*. Retrieved from thinkstep AG: http://database-documentation.gabi-software.com

UNEP. (2016). UNEP-SETAC Life Cycle Initiative . Available Water Remaining (AWARE). *Global Guidance for Life Cycle Impact Assessment Indicators. Volume 1.*

van Oers, L., de Koning, A., Guinée, J. B., & Huppes, G. (2002). *Abiotic resource depletion in LCA.* The Hague: Ministry of Transport, Public Works and Water Management.

Van Zelm, R., Huijbregts, M., & Van de Meent, D. (2009). USES-LCA 2.0: a global nested multi-media fate, exposure and effects model. *The International Journal of LCA, 14 (30)*, 282-284.

Van Zelm, R., Huijbregts, M., Den Hollander, H., Van Jaarsveld, H., Sauter, F., Struijs, J., . . . Van de Meent, D. (2008). European characterization factors for human health damage of PM10 and ozonein life cycle impact assessment. *Atmospheric Environment 42*, pp. 441-453.

Van Zelm, R., Preiss, P., Van Goethem, T., Van Dingenen, R., & Huijbregts, M. (2016). Regionalized life cycle impact assessment of air pollution on the global scale: damage to human health and vegetation. *Atmospheric Environment 134*, 129-137.

WMO. (2009). *cientific Assessment of Ozone Depletion: 2014,Global Ozone Research and Monitoring ProjectReport No. 55.* Geneva, Switzerland.

WMO. (2014). *Scientific Assessment of Ozone Depletion: 2014 ,Global Ozone Research and Monitoring ProjectReport No. 55.* Geneva, Switzerland.

World Aluminium. (2017). *LIFE CYCLE INVENTORY DATA AND ENVIRONMENTAL METRICS FOR THE PRIMARY ALUMINIUM INDUSTRY.* World Aluminium.

WRI. (2011). *GHG Protocol Product Life Cycle Accounting and Reporting Standard.* Washington D.C.: World Resource Institute.

1.10. Critical Review report summary

A critical review was conducted by a panel of three independent experts:

- **Pere Fullana (Chair)** UNESCO Chair in Life Cycle and Climate Change, ESCI-UPF
- **Angela Schindler**, Umweltberatung und Ingenieurdienstleistung (Environmental consultancy and engineering services)
- **Ivo Mersiowsky**, Quiridium

The review panel wants to express their gratitude to both the practitioner and the commissioner for their continuous help and fine work to make the review smooth and sound.

The review panel also wants to state that their task was to check the documents provided by the practitioner (not the models developed or the data used) with the limitations of their accumulated experience and the given time constraints.

This review has been prepared by the review panel with all reasonable skill and diligence, being the result of their opinion on the reviewed study, and by no means a certificate of its quality. The panel is not accountable by any others with respect to any matters related to their opinions. Reactions of any kind made by a third party and based on this review are beyond the panel responsibility.

The unabridged Critical Review Statement can be found in the full report available upon request from the study commissioner.

Having gone through several reviewing rounds which have led to final consensus among all parties, and following ISO 14044 clause 6.1, the critical review panel wants to state that, within their knowledge:

- the methods used to carry out the LCA are consistent with the above International Standards,
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.