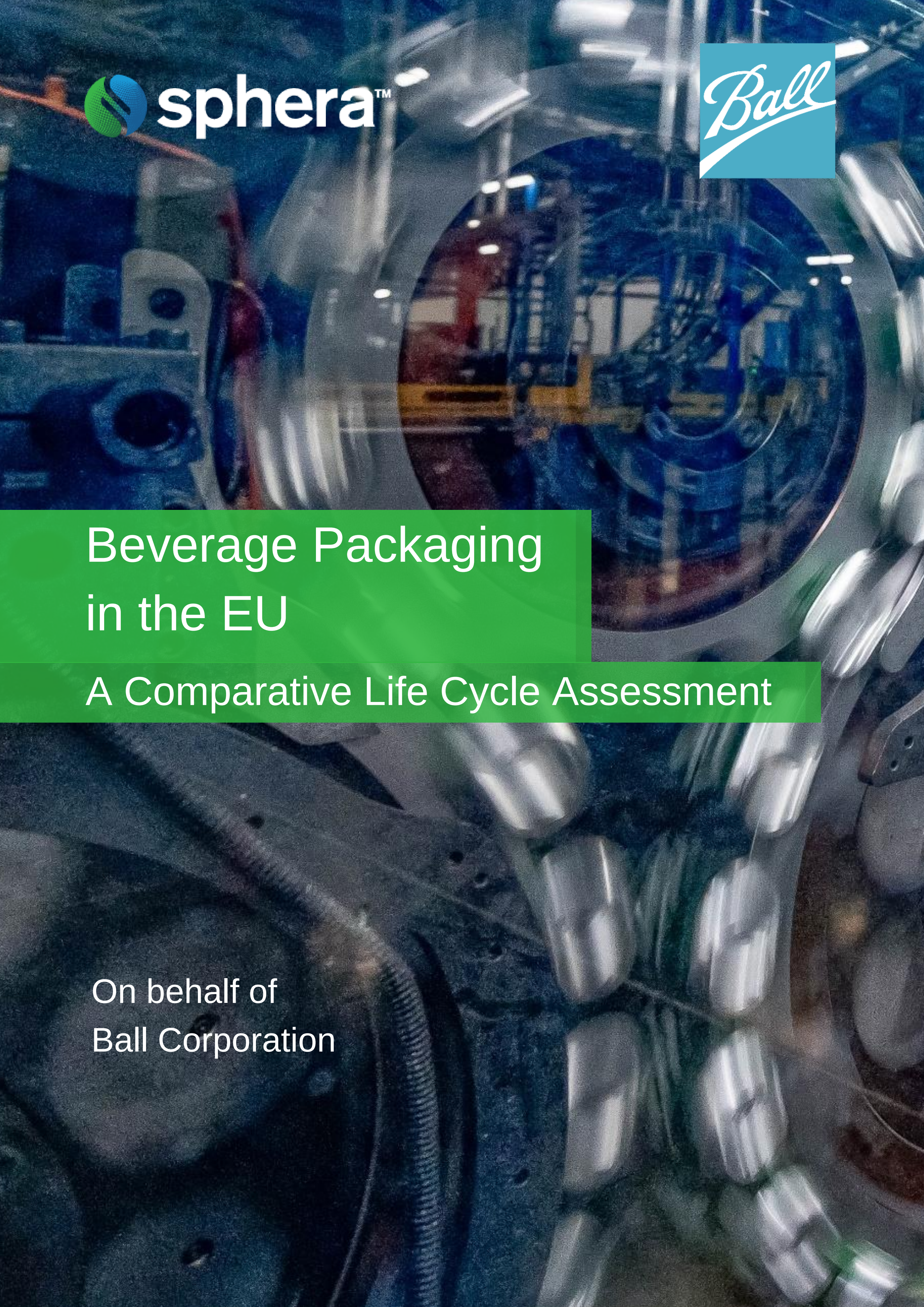

Beverage Packaging in the EU

A Comparative Life Cycle Assessment

On behalf of
Ball Corporation

Client:	**Ball Corporation**
Title:	**Beverage packaging in the EU – A Comparative Life Cycle Assessment**
Report version:	v3.0
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On behalf of Sphera and its subsidiaries

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During the course of the project, thinkstep became Sphera Solutions GmbH. Therefore, all references to 'thinkstep' in this report refer to "Sphera Solutions".

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 EU. 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, 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, and using the Circular Footprint Formula approach developed within the Product Environmental Footprint Guide. 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, product weight and re-usability.
- For non-carbonated beverages, PET bottles show a consistently good performance due to being lightweight, requiring little secondary packaging, and having a relatively low manufacturing energy demand. Beverage cartons perform well due to the main raw material, paperboard (typically around 70% (w/w) of the carton), which tends to have low manufacturing impacts. Among the material options for carbonated beverages, PET bottles are a close match with aluminum cans in terms of climate change. Aluminum cans are lightweight, have a relatively high 69% recycling rate at end of life, while the average level of recycled content is higher than for any other substrate.
- The performance of different packaging types is influenced to some extent by methodological choices, the PEF CFF disadvantaging materials with an already high recycled content, like aluminum.
- 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 format which outperforms all the alternative options across all 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 EU.

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 EU;
- 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 and beverage cartons are resealable. 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 Europe.

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 1 liter 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 EU region (C: carbonated, NC: non-carbonated)

EU					
Baseline			**Additional scenarios**		
Material	**Sizes**	**EoL / Treatment of secondary materials**	**EoL / Treatment of secondary materials**	**Collection rate**	**Others**
Beverage cartons	0.33L	PEF CFF	Substitution	Substitution, Collection rate 0-100%	-
	0.50L				
PET bottle (C)	0.38L	PEF CFF	Substitution	Substitution, Collection rate 0-100%	PET bottle weight reduction by 5-10% Manufacturing energy for blow moulding
	0.50L				
PET bottle (NC)	0.30L				
	0.50L				
Glass bottle (single use)	0.25L	PEF CFF	Substitution	Substitution, Collection rate 0-100%	-
	1.00L				
Glass bottle (refillable)	0.33L	-	-	-	Reuse bottle 0.33L (20x)
Aluminum can	0.25L	PEF CFF	Substitution	Substitution, Collection rate 0-100%	Renewable energy for can manufacturing

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 Ball sites. The competing packaging products also aim to represent current industry averages. The geographical reference is the EU-28 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, section 4.3.4.3. In the EU, the EoL approach of the Product Environmental Footprint (PEF) Circular Footprint Formula (CFF) is adopted for the baseline scenario. The PEF CFF formula aims to find a market-driven balance between the substitution and the cut-off approaches (for more information see the PEF guidance document (European Comission, 2018)). 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 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

This assessment is predominantly based on the compilation of impact categories recommended by the Product Environmental Footprint Guidelines. Implementations in the Life Cycle Assessment software, GaBi 9.2, follow the European Commission Joint Research Centre's characterization factors EF 3.0 published in March 2019.

The PEF framework has gained broad attention from industry and academia alike due to its potential application in future EU regulations, and was therefore deemed as the right set of impacts to evaluate for a study in the European context.

The impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in

Table 3 and Table 4.

Table 3: EF 3.0 impact category descriptions

Impact Category	Description	Unit	Reference
Climate change (GWP100)	A measure of greenhouse gas emissions, such as CO_2 and methane.	kg CO_2 equivalent	(IPCC, 2013)
Eutrophication freshwater	EUTREND model, Fraction of nutrients reaching freshwater end compartment (P)	kg P eq.	(Struijs, van Wijnen, van Dijk, & Huijbregts, 2009)
Eutrophication marine	EUTREND model, Fraction of nutrients reaching freshwater end compartment (N)	kg N eq.	(Struijs, van Wijnen, van Dijk, & Huijbregts, 2009)
Eutrophication terrestrial	Accumulated Exceedance (AE).	Mole N eq.	(European Commission, 2011)
Acidification terrestrial and freshwater	Accumulated Exceedance (AE).	Mole H+ eq.	(European Commission, 2011)
Photochemical ozone formation – human health	Expression of the potential contribution to photochemical ozone formation following the LOTOS-EUROS model.	kg NMVOC eq.	(Van Zelm, et al., 2008)
Ozone depletion	Ozone Depletion Potential (ODP) calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years.	kg CFC-11 eq.	(WMO, 2014)
Ionizing radiation - human health	Ionizing Radiation Potentials: The impact of ionizing radiation on the population, in comparison to Uranium 235.	kBq U235 eq.	(Frischknecht, Braunschweig, Hofstetter, & Suter, 2000)
Land use	Soil quality index based on the LANCA methodology	Pt	(Bos, Horn, Beck, Lindner, & Fischer, 2016)
Cancer human health effects	Comparative Toxic Unit for human (CTUh). Estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kg).	CTUh	(Rosenbaum, et al., 2008)

Impact Category	Description	Unit	Reference
Non-cancer human health effects	Comparative Toxic Unit for human (CTUh). The estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kg).	CTUh	(Rosenbaum, et al., 2008)
Resource use, energy carriers	Abiotic resource depletion fossil fuels (ADP-fossil)	MJ	(van Oers, de Koning, Guinée, & Huppes, 2002)
Resource use, mineral and metals	Abiotic resource depletion (ADP ultimate reserve).	kg Sb eq.	(van Oers, de Koning, Guinée, & Huppes, 2002)
Respiratory inorganics	Disease incidences due to kg of PM2.5 emitted.	Disease incidences	(Fantke, et al., 2016)
Water scarcity	User deprivation potential (deprivation-weighted water consumption)	m^3 world eq.	(UNEP, 2016)

Table 4: Other environmental indicators for the EU 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)
CML2001 Abiotic Depletion (ADP elements)	A measure of the depletion of non-living (abiotic) resources such as fossil fuels, minerals, and clay.	[kg Sb eq.]	(van Oers, de Koning, Guinée, & Huppes, 2002)

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, for example the European Commission put forward the New Circular Economy Strategy to support the EU's transition to a circular economy.

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. 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 manufacturing for 3 sizes/types. Primary data also extended to the secondary packaging for selected final products that use Ball beverage cans.

PET bottles, glass bottles and beverage cartons

For all other beverage containers, secondary data was collected based on sample products selected by Ball for the most relevant market shares in the EU. 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). The precision of weighing scales was worse in one location, affecting 1 PET bottle and 2 glass bottles (potential error up to 5% of the primary packaging as a whole). For carton products produced by Tetra Pak, information on product weight and composition was taken from online resources (Tetra Pak 2019).

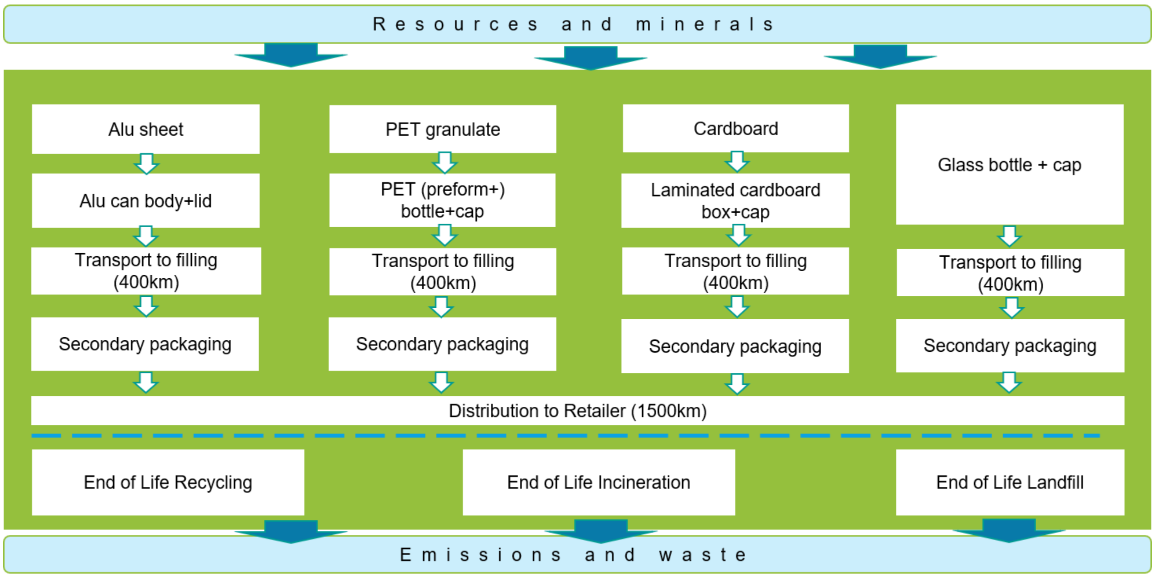

Figure 1: Overview of system boundaries of the product systems investigated, (without displaying details of materials)

Table 5: Overview product specifications

Material	Purchased in	Primary												Secondary		
		Container Volume	Container Weight (g)	DQI*	Cap material	DQI*	Cap Weight (g)	DQI*	Label	DQI*	Label Weight (g)	DQI*	Seal Weight (g)	Nesting	Packaging material	Weight (g)
Carton	UK	0.33L	13.00	L	HDPE	L	4.00	L	direct print	-	n/a	-	n/a	4	corrugated board	20
	DE	0.5L	19.00	L	HDPE	L	4.00	L	direct print	-	n/a	-	n/a	8	corrugated board	126
PET (NC)	UK	0.3L	17.20	M	HDPE	E	3.30	M	LDPE	E	0.4	M	n/a	-	-	n/a
	UK	0.5L	12.90	M	HDPE	E	1.60	M	LDPE	E	0.4	M		12	LDPE	16
PET (C)	UK	0.38L	21.70	M	HDPE	E	3.60	M	LDPE	E	1.9	M	n/a	6	LDPE	8
	DE	0.5L	20.00	M	HDPE	E	2.00	M	LDPE	E	<1	M	n/a	12	LDPE	16
Glass	DE	0.25L	170.00	M	tinplated steel	M	2.00	M	direct print	M	n/a	-	<1	4	corrugated board	44
	DE	0.33L	386.00	M	tinplated steel	M	2.00	M	paper	M	<1	M	<1	24	returnable crate (HDPE)	1770
	UK	1L	518.30	M	tinplated steel	M	1.40	M	paper	M	1.2	M	n/a	6	returnable crate (HDPE)	1042
Alu can	-	0.25L	7.64	M	aluminum	M	2.61	M	direct print	M	n/a	M	n/a	4	corrugated board	28.5
	-	0.33L	9.43	M	aluminum	M	2.44	M	direct print	M	n/a	M	n/a	4	corrugated board	46
														4	LDPE	5
	-	0.5L	11.99	M	aluminum	M	2.44	M	direct print	M	n/a	M	n/a	12	LDPE	15
														12	corrugated board	45

*DQI Data Quality Index: M – Measured, E – Estimated, L – Literature, n/a – not applicable

.

Table 6: Recycled content of considered packaging alternatives

Beverage container	Recycled content	Source
Aluminum	55% can body, 3% can ends	R1, PEF Annex C
PET	0%	R1, PEF Annex C
Glass (flint, colorless)	40%	R1, PEF Annex C
Carton	100% virgin aluminum foil, LPB and polyethylene film	R1, PEF Annex C

Datasets used in the study

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

- Primary aluminum ingot (consumption mix, http://gabi-documentation-2019.gabi-software.com/xml-data/processes/05f94d68-6435-4312-9ae2-091abadc5b24.xml), sheet making (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/1bfa0b24-db14-4785-bf69-35966f2e807e.xml) and recycling (Aluminum remelting, http://gabi-documentation-2019.gabi-software.com/xml-data/processes/a9aa87f8-2daa-4634-83a4-51659ebfb3d5.xml) derive from the latest (2015) European Aluminum association data.

For the PET bottles the most relevant datasets included:

- PET granulate from the EU via PTA pathway (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/4b2420b3-8f56-45f1-984d-173a9298ef4a.xml), mixed with Chinese PET granulate via DMT pathway (ratio 70% EU, 30% CN);
- 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 modelled as Polyethylene high density granulate (HDPE/PE-HD).

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).
- The closures were modelled as tinplated steel (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/6accaea9-92bd-45ee-816e-1037a7f4deb8.xml).

For the beverage cartons the most relevant datasets included:

- The liquid Packaging Board dataset from the ACE/ELCD (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/7d580a76-d2a4-46fe-a3a3-c6c8ed585382.xml)
- The LDPE film has been modelled with virgin granulate (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/27b2f25c-ccec-43cf-97b9-bc97f0f95f49.xml) and plastic film making.
- The aluminum foil has been modelled using the European Aluminum association's ingot (see details under aluminum cans) and film dataset (http://gabi-documentation-2019.gabi-software.com/xml-data/processes/86c4d1c5-19f9-4d43-9bff-0b88b714b93f.xml).

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 EU.

Material	GaBi dataset	Source	Documentation	Reference year
Electricity	EU: Electricity grid mix ts	ts	http://gabi-documentation-2019.gabi-software.com/xml-data/processes/001b3cb7-b868-4061-8a91-3e6d7bcc90c6.xml	2016
Thermal energy from natural gas	EU: thermal energy from natural gas ts	ts	http://gabi-documentation-2019.gabi-software.com/xml-data/processes/cfe8972e-6b51-4a17-b499-d78477fa4294.xml	2016
Thermal energy from fuel oil	EU: thermal energy from light fuel oil (LFO) ts	ts	http://gabi-documentation-2019.gabi-software.com/xml-data/processes/261369f8-8ad9-4cac-81bc-4f308f2d80be.xml	2016

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

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 <u-so>	ts	http://gabi-documentation-2019.gabi-software.com/xml-data/processes/4e47891c-25ca-4263-8ebd-e1b462c0f4b8.xml l	2016
Diesel	EU: Diesel mix at refinery ts	ts	http://gabi-documentation-2019.gabi-software.com/xml-data/processes/244524ed-7b85-4548-b345-f58dc5cf9dac.xml	2016

1.4.1. End of Life

For each product three possible end of life waste streams are available; recycling, incineration (with energy recovery) and landfill. The statistics for each of these recycling streams is based on PEF Guidance Annex C, November 2019. The recycling yields are calculated using GaBi databases. Table 9 below summarizes this information. To be kept in mind is that the cited End of Life shares (%) differ from the recycling rate R2, because the EoL shares include the allocation factor A and the yield of the recycling process.

Transport distances to End of Life processing facilities are neglected, as these are expected to be within 100km radius of the disposal site by the end consumer.

The end of life waste streams are split using consistent calculations for all products. Where material or energy is recovered from end of life processes, fixed material credits are applied to compensate the burdens created by the product life cycles.

Table 9: End of Life statistics applied for the EU region.

Material	EoL stream	EoL share (%)	Recycling rate (%) R2	R2 Definition	Recycling Yield (%)	Allocation factor A	Qs/Qp
Aluminum can	Recycling	56.3	69	Output recycling plant	98	0.2	1
	Incineration	14.0	-	-	-	-	-
	Landfill	17.1	-	-	-	-	-
PET bottle	Recycling	24.6	42	Output recycling plant	86	0.5	0.9
	Incineration	26.1	-	-	-	-	-
	Landfill	31.9	-	-	-	-	-
Glass bottle	Recycling	57.5	66	Output recycling plant	95	0.2	1
	Incineration	15.3	-	-	-	-	-
	Landfill	18.7	-	-			
	Re-use	0-20 re-uses (scenario only)					
Beverage cartons*	Recycling	40.2	43	Input recycling plant	85	0.2	1
	Incineration	25.7	-	-	-	-	-
	Landfill	31.4	-	-	-	-	-

** Beverage carton indicators apply to the liquid packaging board and not to HDPE and aluminum foils in the layers as per direct communication with the dual system in Germany. Fiber losses are considered in the recycling process, therefore Qs/Qp is set to 1.*

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 climate change 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 abiotic depletion potential along with climate change. 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.

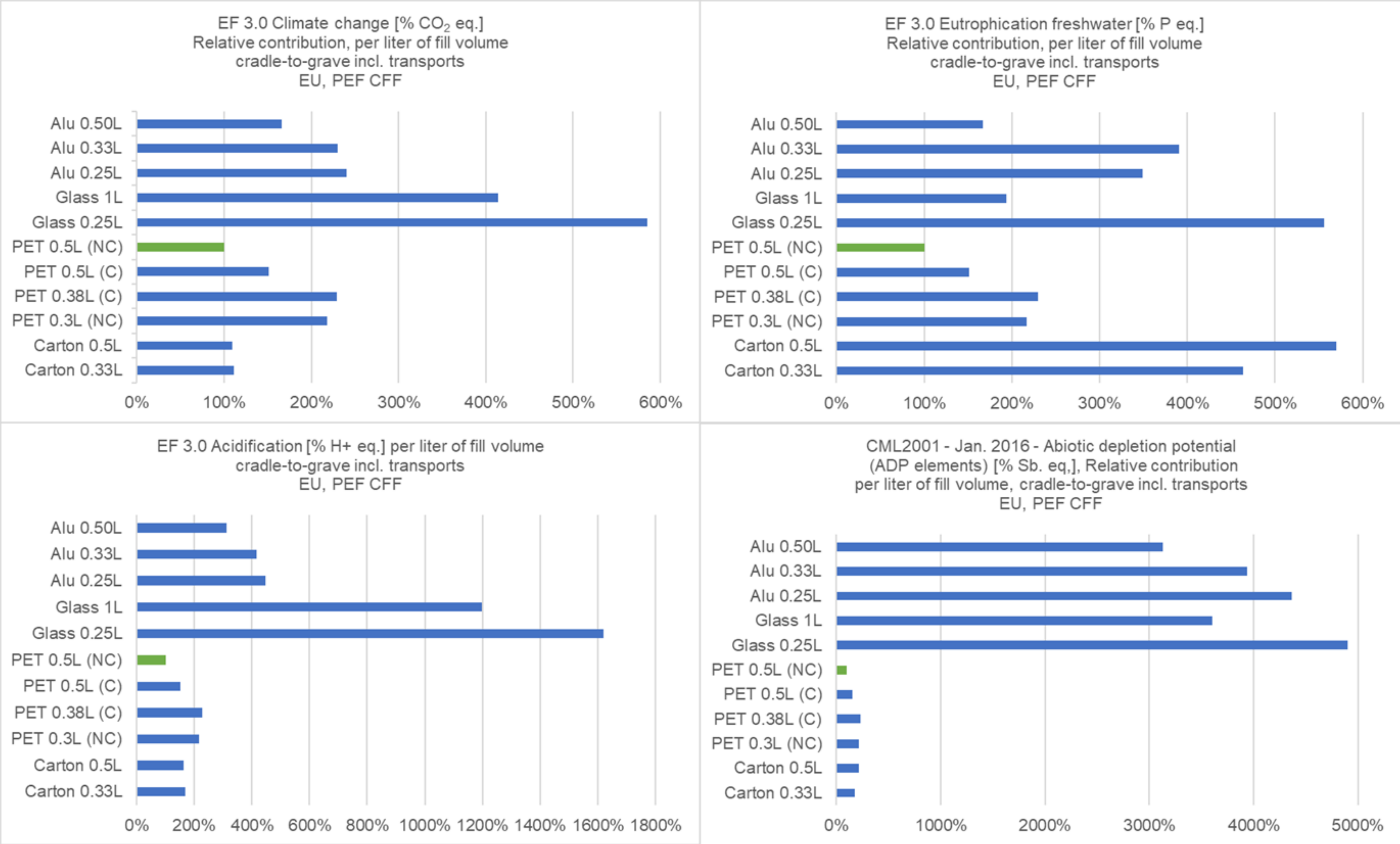

Figure 2: **Overview of selected impact categories explored in the full report. Results refer to the full life cycle (cradle to grave, scaled to liter of fill volume), in relative terms, showing the product with the lowest impact as 100% (in green).**

Climate change – beverage packaging comparison

Climate change is driven by greenhouse gases like CO_2 and CH_4 in the troposphere which trap infrared radiation from 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 the Earth's climates. Greenhouse gases are mainly associated with the combustion of fossil fuels which are used in energy generation and manufacturing of fossil-based materials like plastic.

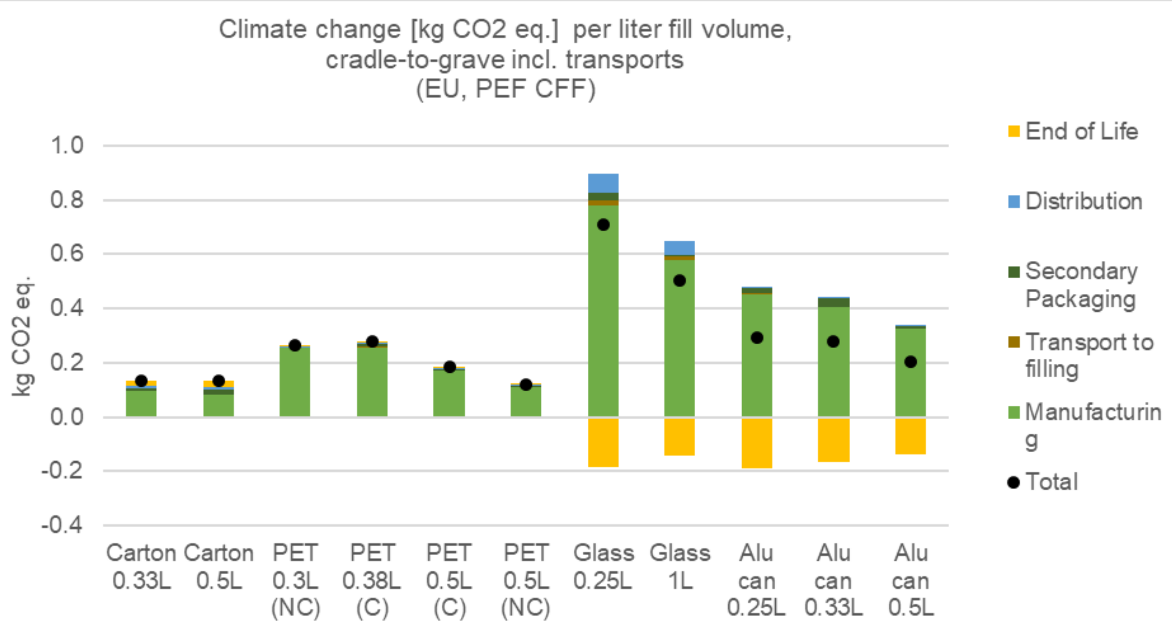

Figure 3: Absolute climate change results of each of the compared products, scaled to 1 liter of fill volume, using the PEF CFF method

Although the 0.5L PET bottle for non-carbonated water has the lowest carbon footprint, due to its very thin walls and consequently low weight, PET bottles for carbonated beverages come with significantly higher carbon emissions. Therefore, beverage cartons show a more consistently low climate change impact, benefitting from the fact that approximately 75% of their mass is composed of virgin paperboard. This is a bio-based material whose 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.). Biogenic carbon dioxide is sequestered during the growth of the trees providing these bio-materials, and is later re-emitted at the end of life which results in a zero overall net emission of greenhouse gases (GHG). The lack of GHG emissions associated with these biomass materials significantly reduces the overall carbon footprint of beverage cartons.

In comparison, PET bottles (except for the above mentioned PET 0.5L bottle for non-carbonated water) have a higher environmental burden associated with their manufacturing stage because they are produced from fossil-based resources, and mainly fossil-fuel derived energy is used during production.

Aluminum cans also have a relatively high impact associated with manufacturing, but this is partly offset at the end of life due to the fact that recycling aluminum saves 95% of the energy compared to the production of virgin aluminum – and because cans have a higher recycling rate compared with other substrates.

Both single use glass bottles show a significantly higher climate change impact than aluminum cans, PET bottles and beverage cartons. This is not surprising given that glass bottle production is very energy intensive and glass bottles are 10x heavier than PET bottles, 15x heavier than beverage cartons and 20x heavier than aluminum cans.

Climate change – aluminum can hotspot analysis

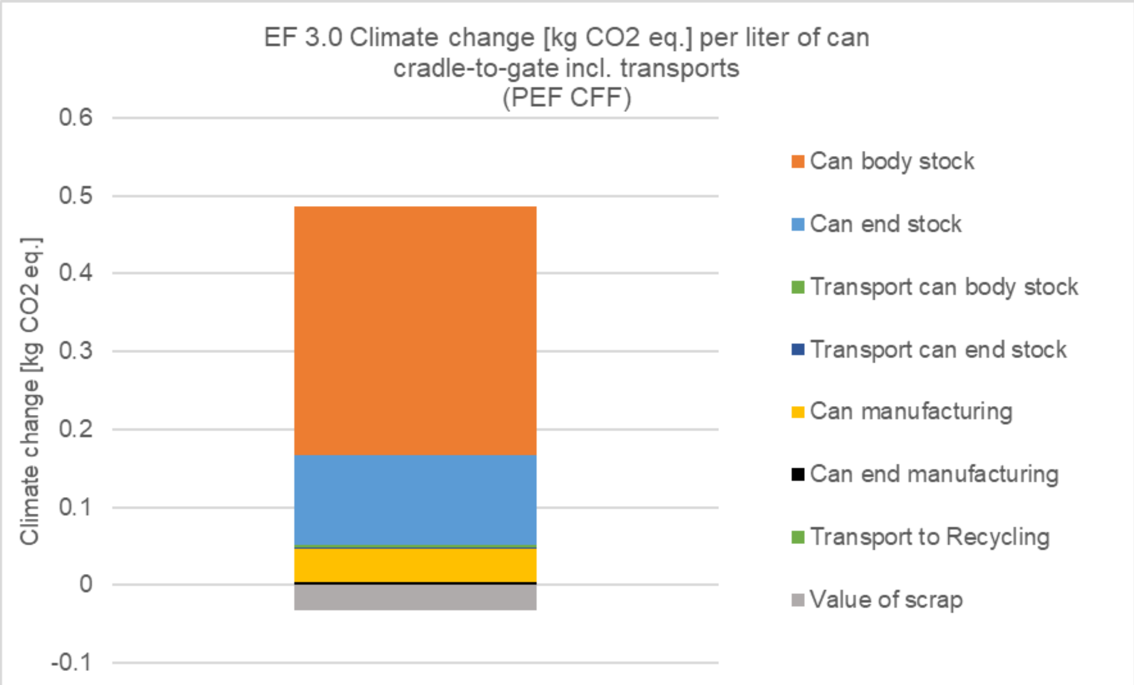

Figure 4: Detailed climate change contributions in the manufacturing phase of the 0.25L aluminum can, shown per liter of fill volume, using the PEF CFF method.

The detailed results show the aluminum and can sheet production, captured as “can body stock,” contributes to more than 60% of the total impact. Most of the impacts for this process are derived from manufacturing the primary aluminum ingot and rolling the aluminum sheet.

20% of the climate change impact stem from “’can end stock,” of which 97% of emissions come from the manufacturing of primary aluminum ingot and rolling the aluminum sheet. While can ends tend to be less than 1/5th of the total can weight, they still represent a significant contribution to the can’s overall carbon footprint because it comes with a lower recycled content compared to the can body (see Annex C of the PEF guidance).

‘Can manufacturing’ contributes 38% to overall climate change impact. This is almost entirely derived from the electricity and thermal energy consumed during these steps. With average European electricity grid mix, energy is largely derived from fossil fuels.

The “value of scrap” aspect refers to the benefits or ‘credits’ assigned to the scrap material which is recycled and re-used as secondary materials. The aluminum can body stock has a relatively high recycled content, and high recycling rate at end of life. For this reason, environmental credits reduce the overall climate change impact.

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 provided in section 0.

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. Two aspects of variation are explored in the results of this study. The first aspect describes the uncertainty in climate change impact for each packaging format assessed, with respect to data quality and methodology. The second aspect describes the potential variability of climate change impact 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 PEF CFF)
- Reuse of the refillable glass bottle (0-20 refills)
- PET bottle manufacturing (2x and 0.5x baseline energy consumption for blow molding)
- PET weight changes (±10%)

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

- Collection rates for recycling 0-100%
- 100% renewable electricity for aluminum can manufacturing

Table 10: Summary of scenario and sensitivity analyses in EU region for EF 3.0 Climate change [kg CO2 eq.] impact of products scaled to 1 liter of fill volume, cradle-to-grave incl. transports, and calculation of uncertainty by means of minimum and maximum values. Grey cells denote the lack of a corresponding scenario / sensitivity analysis.

			Uncertainty						**Future change potential**		
Beverage packaging type	**Sizes**	**Baseline**	**Scenario**	**Sensitivity analyses**					**Scenario**	**Sensitivity analyses**	
		PEF CFF	**Substitution**	**Reuse 20x**	**PET weight 10% increase**	**PET weight 10% decrease**	**PET mfg 2x baseline**	**PET mfg 0.5x baseline**	**Renewable mfg**	**Recycling 0%**	**Recycling 100%**
Beverage cartons	0.33L	0.13	0.13								
	0.5L	0.13	0.13							0.14	0.11
PET bottles	0.38L (C)	0.28	0.25		0.30	0.25	0.32	0.26			
	0.50L (C)	0.18	0.17		0.20	0.17	0.21	0.17		0.21	0.10
	0.30L (NC)	0.26	0.24		0.29	0.24	0.30	0.25			
	0.50L (NC)	0.12	0.11		0.13	0.11	0.14	0.11		0.14	0.07
Glass bottles	0.25L	0.71	0.69								
	1.00L	0.50	0.49							0.70	0.38
	0.33L (refill)	1.14		0.24							
Aluminum cans	0.25L	0.29	0.24						0.27	0.49	0.13
	0.33L	0.28	0.24						0.26	0.46	0.14
	0.50L	0.20	0.17						0.18	0.34	0.09

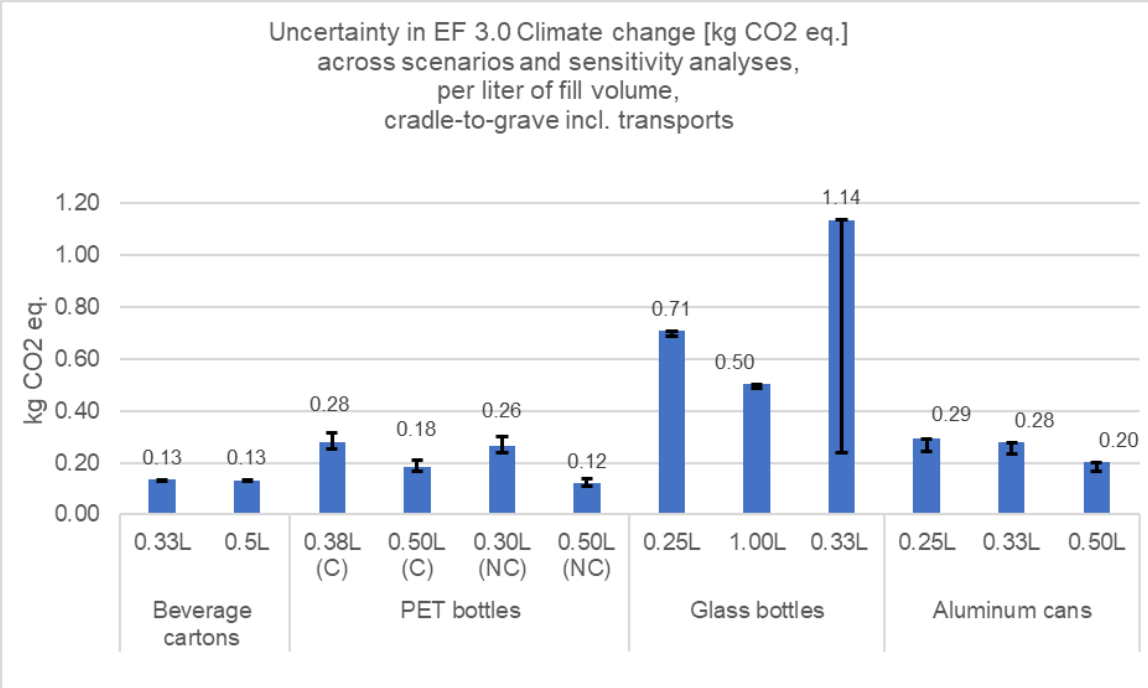

Figure 5: Uncertainty analysis of the EF 3.0 Climate change [kg CO2 eq.] impact of products, scaled to 1 liter of fill volume, based on the results of the recycling methodology scenario and sensitivities to glass bottle refilling, and variation in PET manufacturing energy consumption. Values taken from Table 10: baseline - PEF CFF, 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”.

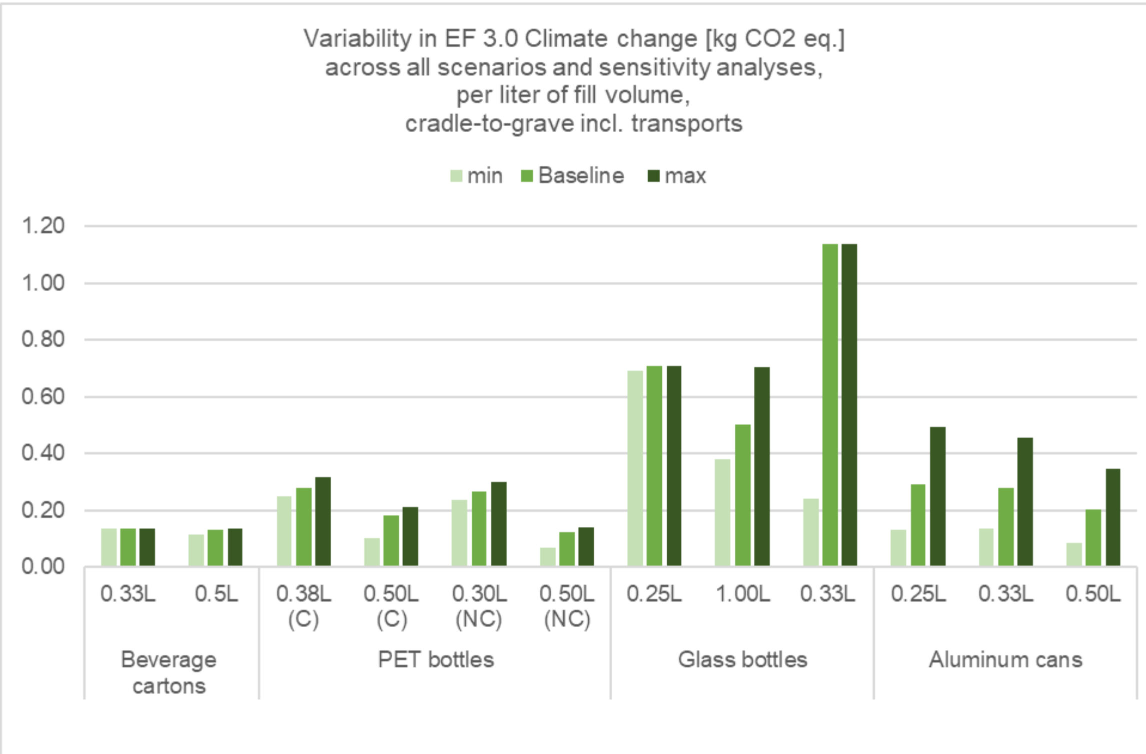

Figure 6: Variability of the EF 3.0 Climate change [kg CO2 eq.] impact of products scaled to 1 liter of fill volume, cradle-to-grave incl. transports, across all scenarios and sensitivity analyses in the EU.

There is little recorded uncertainty for beverage cartons (Figure 5), and no significant improvement potential found exploring future directions of change (Figure 6). This is because the cartons are not significantly affected by changes to the recycling rate, nor to methodological differences in the underlying recycling methodology for the study.

PET bottles show a considerable 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 weight differences. The PET bottles do show a medium response to improvements in the recycling rate (Figure 6).

The 0.25L and 1L single-use glass bottles do not show any uncertainty in Figure 5, but the larger bottle demonstrates a marked potential for improvement if collected for recycling at higher rates (Figure 6). The refillable 0.33L glass bottle shows the highest level of uncertainty out of all packaging formats due to the unknown number of actual refill trips per bottle.

Aluminum cans demonstrate a small degree of uncertainty, which is derived from differences in the climate change impact found for the baseline recycling methodology and alternative (substitution) recycling methodology. Cans have a high potential for improvement based on the recycling rate and switching the electricity grid mix supply used for manufacturing from fossil-based to renewable.

The potential improvements identified for each packaging type may be considered more attainable as recycling and reuse regulations are changing rapidly, driving the packaging sector towards real circularity.

1.7. Material Circularity Indicator

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 relatively high MCI scores of ~0.7, which reflects the highest average recycled content (55% of can stock, 3% of end and tab stock) and end of life recycling rate (69%) of all beverage packaging materials. The 0.5L cans have a slightly lower MCI score because the cans chosen for this study came with slightly heavier PE film as secondary packaging.

Beverage cartons have an intermediate MCI score of 0.5-0.6. The cartons have a lower collection rate of 43%, and only the paper fractions are assumed to be recycled. However, the cartons are ~70% paperboard which has 0% recycled content but is assumed to be sustainably sourced and therefore considered completely restorative by the MCI methodology. This greatly benefits their MCI score. The 0.5L carton has a higher MCI score because it requires a greater quantity of cardboard secondary packaging. The secondary packaging used is also assumed to be sustainably sourced and comes with a high recycling rate. Conversely to the basic principles of LCAs, material efficiency considerations and waste treatment, the use of additional material in this case is rewarded in the MCI score, purely because of its renewable origins. Provided that the carton in the primary packaging is not sourced sustainably, the MCI would be considerably lower. It is not a matter of this report to discuss this methodological principle, but the authors advise the use of caution when interpreting MCI values and making decisions without additional considerations.

PET bottles have the lowest MCI score (below 0.3). This reflects the 0% recycled content or re-use. The MCI scores are driven mainly by the relatively low recycling rate at end of life of 42%.

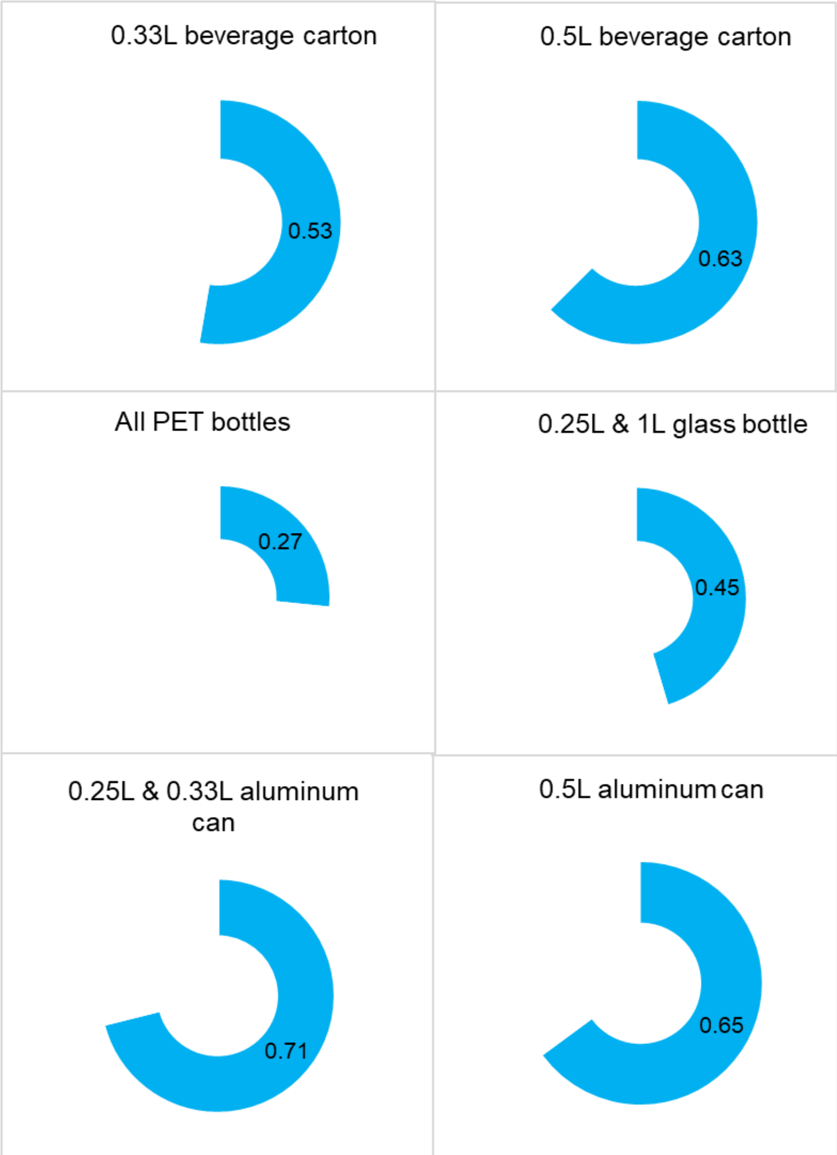

Figure 7: Material Circularity Indicator results for the different packaging options (EU)

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 0.5L PET bottle for non-carbonated water, due to a very thin-walled bottle design, resulting in a favorable packaging-to-product ratio.
- As a material option for all non-carbonated beverages, however, beverage cartons perform more consistently well in climate change and acidification.

- The strong performance of beverage cartons is primarily due to the main raw material, paperboard (typically around 70% (w/w) of the carton), which tends to have low manufacturing impacts. If paperboard is produced in an integrated pulp and paper mill, most of the energy used will be derived from biomass such as wood offcuts from forestry, from 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.
- Among the material options for carbonated beverages, PET (C) bottles are a close match with aluminum cans in terms of climate change. In terms of eutrophication, acidification and blue water consumption PET performs better. 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.
- Aluminum cans are lighter than other packaging options, which helps to reduce impacts. At 69%, the recycling rate at end of life is high, while the average level of recycled content is higher than for any other substrate. Interestingly, while prescribed recycled content and recycling rates were directly taken from the PEF Guide and its Annex C, the latest data from European Aluminium reveals a higher recycling rate for beverage cans across Europe of 75%. Taking the higher recycling rate would decrease the impact of aluminum cans further.
- The performance of different packaging types is influenced to some extent by methodological choices. The PEF CFF approach does not favor aluminum cans, 20% of the amount sent to recycling will be treated as cut-off, i.e. without material credit. On the input side, the formula accounts 80% of the recycled content as primary aluminum, thus increasing the impact overall. Importantly, the same approach does not disadvantage beverage cartons in terms of carbon footprint, because the virgin paper has an even better carbon footprint than the recycled one. By contrast, when using the alternative substitution approach, the high end of life recycling rate of aluminum reduces the relative difference to cartons, which have a much lower end of life recycling rate of only 43% (of fiber inputs only). Using the substitution approach instead of the baseline PEF CFF benefits PET bottles as well, but to a lesser degree than aluminum cans.
- Improvement of recycling rates has further potential to reduce the gap between beverage cartons and aluminum cans. While aluminum cans are fully recyclable (yield of 98%), the potential improvement for cartons is far less. This is because recycling facilities - unlike virgin paper production - need to rely on external energy sources, therefore a higher recycling rate does not currently improve the performance of cartons in terms of climate change. Even though a 100% collection rate is unfeasible, this finding does demonstrate the environmental benefits of focusing on driving up recycling rates further at end of life – meaning that, for aluminum cans, circular economy enhancements and climate protection go hand in hand.
- Cans can accrue a further ~10% improvement once can manufacturing electricity provision is fully based on renewable energy. Certainly, other packaging formats would also benefit from full reliance on renewable energy, most notably PET bottles and to some extent glass, which is, however, primarily reliant on thermal energy. Since the beverage cartons as modeled in this study are already benefiting from the renewable energy supplied by virgin pulp by-products, they are less likely to benefit to a large extent.
- Recycling rate improvements also offer high potential improvement for glass bottles (>20% improvement of the carbon footprint at 100% collection), although relative to the competing packaging alternatives, single-use glass can only improve its carbon footprint up to the level of PET bottles. Reuse at the end of life has an even larger potential. When reused 5 times,

glass bottles reach the same reduction in mentioned category as with 100% collection, whereas reusing them 20 times, a glass bottle's impact can be reduced by ~80% even considering the increased weight required for reusability.

- The environmental performance, especially carbon footprint, of PET bottles can be improved with higher real recycling rates, although the full potential of improvements would have to include a proportionally higher recycled content as well. Current PEF values estimate recycled content (R2) at 0. We have also seen the influence of thin wall designs (bottle for non-carbonated water) on the climate change impact category: reduction in material used goes hand in hand with reduction of environmental impacts.
- Although manufacturing of the primary packaging dominates most impact categories, secondary packaging does become dominant in the impact category eutrophication, where carton in secondary packaging contributes more than half of the total life cycle of aluminum cans and glass bottles due to the amount of waste water produced in 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. In the European LCA, non-carbonated PET bottles also include a juice bottle, which comes with significantly more weight and environmental impacts. This means that beverage cartons perform more consistently well overall for non-carbonated beverages.
- PET bottles perform well in most impact categories due to being relatively 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. Returnable bottles would predictably have a significant potential to improve the impact of these packaging systems as well.
- 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. However, this is a correlation only and 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. 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. Beverage cartons perform quite well primarily due to their renewable main raw material, paperboard. A near-perfect MCI can be achieved by refillable glass bottles, if in fact refilled many times. Attention must be paid when comparing MCI scores because material efficiency during production processes is not considered by this indicator. Therefore, it is strongly recommended that any statement or decision based on the MCI should be supported by environmental indicators.
- 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.

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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.